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DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-78-21

EFFECTS OF TURBIDITY AND SUSPENDED MATERIAL IN AQUATIC ENVIRONMENTS

LITERATURE REVIEW

by

Edward M. Stern
Department of Biology
University of Wisconsin
Stevens Point, Wisconsin 54481

and

William B. Stickle
Department of Zoology and Physiology
Louisiana State University
Baton Rouge, Louisiana 70803

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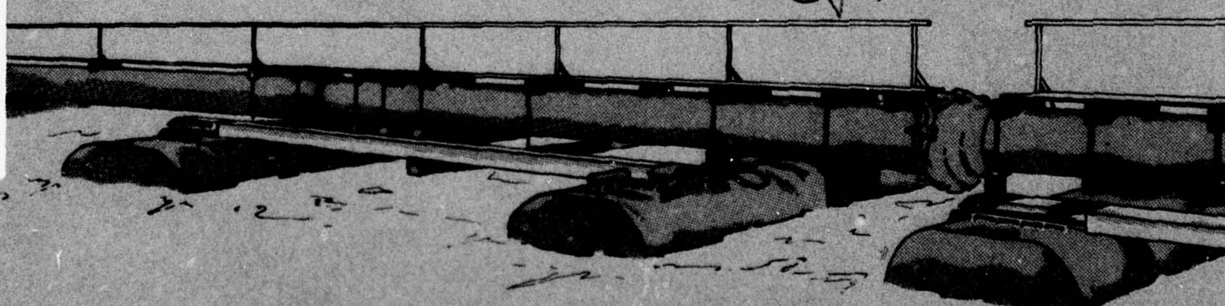

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1. The work reported herein was undertaken as Work Unit 1D01 of Task 1D, Effects of Dredging and Disposal on Aquatic Organisms, of the Corps of Engineers' Dredged Material Research Program. Task 1D was a part of the Environmental Impacts and Criteria Development Project (EICDP), which had a general objective of determining on a regional basis the direct and indirect effects on aquatic organisms due to dredging and disposal operations. The study reported herein was part of a series of research contracts developed to achieve the EICDP general objective.

2. This report is a review of the literature on the environmental effects of turbidity, particularly in relation to dredging. The discussion covers definitions and measurement techniques, origins, and effects on aquatic environments. The environmental effects of turbidity and suspended material can be either beneficial or detrimental. Water quality is partially determined by a number of reactions with suspended material that function in the adsorption, transportation, and desorption of heavy and trace metals, pesticides, and nutrients.

3. Turbidity and suspended material may reduce photosynthetic activity by interference with light penetration, but primary production can also be stimulated through the addition of nutrients associated with particulates. Turbidity and suspended material can variously affect aquatic animals. Turbidity and suspended material are usually detrimental to coral reefs through the reduction of feeding activities and the reduction of light available to the symbiotic coralline algae. Most studies on adult estuarine and marine bivalve molluscs (clams, oysters, and mussels) have indicated that, except for individuals directly buried by the disposal operation, the mortality rate among populations adjacent to dredging and disposal areas is low. However, the percentage of normally developing eggs and larvae may decrease as the concentration of suspended solids increases in the range of concentrations normally resulting from dredging and disposal. Suspended solids can be responsible for a delay of several hours in the hatching time of fish eggs. Adult fishes as a group are more sensitive to suspended solids than most invertebrates; however, in most studies of the effects of dredging and disposal operations on fishes, patterns of seasonal occurrence, abundance, and species diversity generally remained similar to the controls.

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4. The literature indicates that turbidity and suspended solids conditions typically created by most dredging and disposal operations are of short duration and are unlikely to produce severe and irreversible ecological effects; possible exceptions to this generalization are coral reefs and other communities especially sensitive to turbidity. Any possible effects of turbidity and suspended material in aquatic environments may be further minimized by carefully selecting disposal sites, keying operations to seasonal cycles in biological activity, and giving special consideration to areas that serve as nursery grounds.

5. The information in this report summarizes the present knowledge of the environmental effects of turbidity. It is expected that this information will be of significant value to those concerned with selecting an environmentally compatible disposal alternative for dredged material.

John L. Cannon
JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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This literature review of the effects of turbidity and suspended material in aquatic environments covers the following subjects: definitions, units of measure, and methods of measurement; origins; and effects in aquatic environments.

Turbidity, regardless of the multiplicity of definitions, units of measure, and methods of measurement, is an expression of the optical properties of water

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that cause light to be scattered and absorbed rather than transmitted in a straight line. Turbidity is not the same as siltation, although the terms have been used synonymously in the past. The various units of measure include the Jackson Turbidity Unit (JTU), Formazin Turbidity Unit (FTU), and Nephelometric Turbidity Unit (NTU). The methods of measuring percent transmission or the weight per volume concentration of suspended particulates are based on either gravimetric or optical techniques.

Turbidity and suspended material in the aquatic environment are the result of both natural processes and the activities of man. Land erosion is the major source, with agricultural activity contributing the bulk of the material. Additional sources include the resuspension of bottom sediments, dredging and the disposal of dredged material, and turbidity maxima and currents.

The environmental effects of turbidity and suspended material are both beneficial and detrimental. Water quality is partially determined by a number of reactions with suspended material that function in the adsorption, transportation, and desorption of heavy and trace metals, pesticides, and nutrients.

Turbidity and suspended material may reduce photosynthetic activity by interference with light penetration. However, primary production can also be stimulated through the addition of nutrients associated with particulates.

Turbidity and suspended material variously affect aquatic animals. Among coelenterates, turbidity and suspended material are usually detrimental to coral reefs through the reduction of feeding activities and the reduction of light available to the symbiotic coralline algae.

Bivalve molluscs (clams, oysters, mussels), as filter feeders, play an important role in reducing turbidity in natural systems by removing suspended materials from the water column. Most studies on adult estuarine and marine bivalves have indicated that, except for individuals directly buried by the disposal operation, the mortality rate among populations adjacent to dredging and disposal areas is low. By contrast, laboratory studies indicate that the percentage of normally developing eggs and larvae usually decreases as the concentration of suspended solids increases in the range of concentrations normally resulting from dredging and disposal.

Laboratory studies of several species of crustaceans (crabs, lobsters, shrimp) and fishes have indicated that suspended solids, temperature, and dissolved oxygen can interact in a highly complex, nonadditive manner to influence survival time. Adult fishes as a group are more sensitive to suspended solids than most invertebrates. However, in most studies of the effects of dredging and disposal operations on fishes, patterns of seasonal occurrence, abundance, and species diversity generally remained similar to the controls. Suspended solids can be responsible for a delay of several hours in the hatching time of fish eggs.

The literature indicates that turbidity and suspended solids conditions typically created by most dredging and disposal operations are of short duration and are unlikely to produce severe and irreversible ecological effects: possible exceptions to this generalization are coral reefs and other communities especially sensitive to turbidity. Any possible effects of turbidity and suspended material in aquatic environments may be further minimized by careful selection of disposal sites; keying operations to seasonal cycles in biological activity; and special consideration of areas that serve as nursery grounds.

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SUMMARY

Turbidity is a water quality parameter that is routinely measured as part of most fresh, estuarine, and coastal research programs and monitoring surveys. This review of the literature on the effects of turbidity and suspended materials in aquatic environments covers the literature through 1973, with the inclusion of selected references through 1977. It includes discussions of definitions, units of measure, and methods of measurement of turbidity and suspended material; origins of turbidity and suspended material; and effects of turbidity and suspended material in aquatic environments.

Definitions, Units of Measure, and Methods of Measurement of Turbidity and Suspended Material in Aquatic Environments

Turbidity is a result of the presence of suspended material such as clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms. Collectively these particles interfere with the transmission of light through a liquid medium. Confusion concerning turbidity is a result of the multiplicity of definitions, units of measure, and methods of measurement, many of which are not equivalent or interchangeable. The concept of turbidity relates to the optical properties of water that cause light to be scattered and absorbed rather than transmitted in a straight line.

Numerous definitions, units of measure, and methods of measurement have been applied to turbidity and suspended material in aquatic environments. Because the concept of turbidity involves optical properties that cannot be correlated with the weight/volume concentration of suspended material, which directly affects an aquatic fauna, several investigators have suggested that the term be used only as a nontechnical appearance descriptor.

Most of the currently used methods of measurement of turbidity and suspended material are either gravimetric measurements or optical measurements based on either standard suspensions of known turbidities or

on the absolute measurement of some optical property. There is common agreement that the optical instruments in use provide an inferred rather than a direct measurement of suspended solids and that it is almost impossible to transfer the relationships between sediment concentrations and optical characteristics from one type of turbidimeter, standard suspension, or unit of measure to another. Gravimetric techniques probably represent a more accurate measurement of the effects of suspended solids on the aquatic fauna while optical measurements may be preferable for photosynthetic or aesthetic purposes.

Origins of Turbidity and Suspended Material in Aquatic Environments

Turbidity and suspended material are the results of both natural processes and human activities. Land erosion, primarily as a result of agricultural activities, is the greatest cause of turbidity in most lakes, rivers, and estuaries in the United States, with about 500 million short tons of sediment carried into the sea each year. The resuspension of bottom sediments as a result of wave action, currents, and winds is an important source of turbidity. Additional sources of turbidity include turbidity maxima, turbidity currents, biological sources (plankton blooms, red tides, organic detritus, and the foraging of aquatic animals), and the discharge of various wastes such as dredged materials, industrial wastes, and sewage sludge.

There are a number of natural physical, chemical, and biological turbidity-reducing processes. The chief physical processes are settling and dispersion. Biological processes include the removal of suspended particles by filter-feeding organisms and vegetative cover that exerts a stabilizing effect and retards the resuspension of bottom sediments.

Effects of Turbidity and Suspended Material in Aquatic Environments

The responses of aquatic organisms to turbidity and suspended material are frequently difficult to determine because they may be due to a wide variety of causes, including the following: concentration of

suspended solids or the number of particles in suspension, their densities, size distribution, shape, mineralogy, sorptive properties, or presence of organic matter and its form; inherent physical, chemical, and biological characteristics of each site; and antagonistic and synergistic effects. Although in much of the older literature the effects of siltation and suspended materials on aquatic organisms were considered to be synonymous, the two processes are quite distinct and in this review only the latter is discussed.

It is often difficult to assess the effects of turbidity and suspended material on aquatic organisms. Other conditions frequently affect aquatic organisms before and during the increase in turbidity and suspended solids, as illustrated by the complex interaction between the solids, temperature, and dissolved oxygen on invertebrates and fishes. Laboratory experiments often do not duplicate natural conditions or reflect natural levels of tolerance. Several investigators have demonstrated that suspensions of dredged material that affected organisms in the laboratory produced no detectable changes when encountered in the same concentrations in nature. In other studies, higher concentrations of resuspended natural sediments were required to cause the same effects obtained with suspensions of processed mineral solids of known composition, particle size distribution, and organic matter content.

Water quality

A number of reactions (sorption, precipitation, flocculation, and aggregation) are of ecological importance. They function in the adsorption, transportation, and desorption of heavy and trace metals, pesticides, and nutrients in fresh and estuarine waters.

Metals in proper concentrations are important in the physiology of all living organisms while excessive concentrations of such metals as mercury, arsenic, and lead can be toxic. The relationship between heavy metals and dredging and dredged material disposal is not fully known.

Pesticides are sorbed and desorbed by both organic and inorganic suspended sediments, with the clay mineral content being one of the

more important inorganic constituents. Although a substantial amount of information is available in the literature on the effects of dissolved pesticides in the aquatic environment, there is a paucity of information that directly deals with dredging or dredged material disposal operations.

Nutrient uptake and release by suspended materials have also been closely studied. Most investigators agree that the mixing of sediments and resultant suspension accelerates the exchange process. The release of nutrients, which may occur during dredging operations, can be both beneficial (release valuable nutrients) and detrimental (stimulate biological growth such as algal blooms and red tides).

Another water quality parameter that is affected by turbidity and suspended material is dissolved oxygen. Most field monitoring studies adjacent to dredging operations have revealed depressions of oxygen content of the receiving waters. These conditions were usually found only near the bottom near the point of discharge and were of short duration as a result of rapid mixing of dredging and disposal site water with the surrounding water.

Primary production

Numerous studies have examined the effects of turbidity and suspended material on the development of phytoplankton populations. The most frequently cited negative aspect is the reduced photosynthetic activity due to the interference of light penetration. However, the addition of suspended material can also stimulate photosynthesis by increasing the available nutrients. One of the most poorly understood aspects of dredging and disposal of dredged material is the relationship between these activities and primary production. Little is known about the time duration of turbidity from dredging versus the time necessary for algal stimulation. Most of the investigators that considered the effects of dredging and disposal of dredged material on primary production reached the general conclusions that the reduced water transparency was of short duration and that these activities resulted in the release of beneficial nutrients. In several studies, wind-induced turbidity had a greater impact than that typically caused by dredge effluents.

Selected Phyla of Invertebrates

Relatively few studies relate animal responses to the actual weight per volume concentration of particles in suspension; rather, they correlate response with turbidity even though it is unlikely that the light absorbing and scattering properties of suspended particles directly affect animals. The effects of turbidity and suspended material on aquatic invertebrates have been studied in the field and in the laboratory using both natural and processed sediments. However, most of this research has concentrated on a relatively few commercially important species.

Among members of the phylum Coelenterata, the corals have been the most extensively studied. Large concentrations of suspended material and increased turbidity are usually detrimental to coral reefs through the interference of feeding activities of the coral polyps and the reduction of the light available to the symbiotic coralline algae. Using ciliary action, some species of coral are capable of removing suspended material from their surfaces. In general, the tolerance to turbidity and suspended material is apparently quite variable with the reefs in some turbid waters differing ecologically and structurally from the ones in clearer waters.

Many species of the phylum Mollusca, particularly the members of the class Bivalvia (clams, oysters, mussels), are filter feeders and play an important role in reducing turbidity by removing suspended materials from the water column. Because bivalves are more or less stationary, they frequently respond to increased levels of turbidity and suspended sediment by tightly sealing their valves. Thus they may survive adverse conditions for several days by avoiding direct contact with the surrounding water.

Most of the work on estuarine and marine bivalves has involved the adults. In most studies where bivalves were suspended in baskets adjacent to dredging and disposal operations, mortalities were low. Bivalve populations directly below the discharge point were usually killed as a result of siltation or burial.

As filter feeders, bivalves are susceptible to the mechanical and

abrasive action of suspended sediments. With increased concentrations of suspended solids, there is frequently a reduction in pumping rate, clogging of the animal's filtering apparatus, and a subsequent reduction in growth rate. However, when the flow of turbid water is replaced by regular seawater, normal pumping rates usually resume.

The effects of turbidity-producing materials on the development and growth of bivalve eggs and larvae are usually directly related to the concentration. Although some clam eggs will develop normally in concentrations of clay, fuller's earth, and chalk up to 4 g/ℓ, the percentage developing normally decreases as the concentration increases.

Among members of the phylum Arthropoda, the most closely studied species have been those in the class Crustacea (crabs, lobsters, shrimp, barnacles). The effects of turbidity and suspended sediments on the species of crustaceans studied to date are highly variable. For several species of adult copepods, suspensions of fuller's earth, silica sand, and natural sediments in combination with suspensions of phytoplankton caused reductions in feeding rates because the zooplankters were unable to feed selectively. Suspended sediment concentrations also reduced the ability to molt through various larval stages.

In a study on the reproductive rate of the water flea, *Daphnia magna*, small amounts of suspended material were essential to optimal reproduction and survival. When mortalities were noted at higher concentrations of suspended sediments, it was concluded that the toxic effect was a result of the adsorptive capacity of the sediments.

Recent data for the sand shrimp, *Crangon nigricauda*, indicate that suspended solids concentration, temperature, and dissolved oxygen can interact in a highly complex, nonadditive manner to influence survival time. Survival was highest under conditions of low temperature and suspended solids and high dissolved oxygen. The influence of temperature and dissolved oxygen was evident by the fact that survival at 45 gm/ℓ, 10°C, and 5 ppm dissolved oxygen did not differ significantly from that at 0 gm/ℓ, 18°C, and 2 ppm dissolved oxygen.

Fish

Turbidity and suspended material affects fishes directly and

indirectly and this review considers only the former. Direct effects include lethal agents and those factors that influence physiological activities (reproduction, growth, development) or produce abrasive wear on tissues.

In one study, 16 species of adult fishes were exposed to concentrations of montomorillonite clay ranging up to a turbidity equivalent to that produced by 225,000 ppm standard silica flour. Abnormal responses (momentary swimming at the surface and gulping for air) were observed at a concentration equivalent to about 20,000 ppm silica flour and death occurred at turbidities equivalent to 175,000 to 225,000 ppm silica flour. Most individuals endured exposure to turbidities equivalent to 100,000 ppm silica flour for over a week. In those fishes that succumbed, the opercular cavities and gill filaments were clogged with clay particles. Other investigators have observed a thickening of the gill lamellae, excessive mucus secretion, abrasion of the branchial epithelium, and respiratory distress as a result of exposure to high suspended solids concentrations.

Recent data, based upon weight/volume concentrations of suspended solids, from several closely monitored laboratory studies are probably more indicative of the natural responses of adult fishes to suspended solids. The results of these studies have indicated the following: adult fishes, as well as invertebrates, are affected by a complex interaction between suspended solids, temperature, and dissolved oxygen; although the lethal concentration to which 10 percent of the individuals will be killed (LC_{10}) is known, it is not possible to predict the magnitude of the LC_{20}, LC_{50}, etc.; a correlation exists between normal habitat and sensitivity to suspended solids with the most tolerant species being the bottom dwellers while the filter feeders are the most sensitive; high suspended solids concentrations would be less harmful in winter than in summer, and fishes as a group are more sensitive to suspended solids than many of the invertebrates studied to date.

In most field investigations of the effects of dredging on fishes, some fishes usually migrated out of the dredging area, but gross effects to fishes were rarely observed. Patterns of seasonal occurrence and

abundance, species diversity, and histology of the branchial epithelium among fishes exposed to dredging operations and dredged material disposal generally remained similar to the controls.

Several laboratory studies on the reproduction, growth, and development of fishes indicated that for fish eggs incubated in suspensions of varying concentrations there was frequently a delay of several hours in the time of hatching. It was concluded that in nature in a relatively well-mixed environment, concentrations of natural fine-grained suspended sediment up to about 500 mg/ℓ would not affect hatching success for the yellow perch, white perch, striped bass, and alewife. However, within a given species, the juveniles generally were more sensitive to concentrations of suspended solids than the adults.

Summary and Conclusions

Because the most widely accepted definition of turbidity stresses optical properties that cannot be correlated with the weight/volume concentration of the suspended material that directly affects an aquatic fauna, several investigators have suggested that the term be used only as a nontechnical appearance descriptor. There is common agreement that the optical instruments in use provide an inferred rather than a direct measurement of suspended solids. Gravimetric techniques probably represent a more accurate measurement of the effects of suspended solids on the aquatic fauna while optical measurements may be preferable for photosynthetic or aesthetic purposes.

Turbidity and suspended material can play both a beneficial and detrimental role in aquatic environments. Suspended material sorbs and removes contaminants from the water column and stimulates photosynthesis through the introduction of inorganic nutrients. However, there is always the possibility that the nutrients might stimulate excessive biological growth and that turbidity might reduce photosynthetic activities because of its interference with light penetration.

Turbidity and suspended material affect invertebrates in a variety of ways, with the filter-feeding invertebrates the most frequently and

adversely affected. Most studies have indicated that upon exposure to temporary increases in turbidity and suspended material, similar to those encountered in areas where dredging or the disposal of dredged material has occurred, no permanent effects were exhibited. As a group, fishes are more sensitive to suspended solids than are most invertebrates.

A number of investigators have suggested guidelines for dredging operations and the disposal of dredged material that would help to minimize the possibility of adverse effects of turbidity and suspended material. These include careful selection of disposal sites; conducting operations during periods of low biological activity; and special consideration and planning for areas that serve seasonally as vital migratory routes or nursery grounds.

PREFACE

This literature review of the effects of turbidity and suspended material in aquatic environments covers the literature through 1973 with inclusion of selected work through 1977. The work was accomplished during 1977 as part of the Dredged Material Research Program (DMRP) Task 1D, "Effects of Dredging and Disposal on Aquatic Organisms," Work Unit 1D01, "Effects of Turbidity and Suspended Material in Aquatic Environments." This study was conducted at the University of Wisconsin, Stevens Point, Wisconsin, for the U. S. Army Engineer Waterways Experiment Station (WES). The DMRP was sponsored by the Office, Chief of Engineers, U. S. Army, and managed by the Environmental Laboratory (EL), WES.

This report was co-authored by Dr. Edward M. Stern, Department of Biology, University of Wisconsin, and Dr. William B. Stickle, Department of Zoology and Physiology, Louisiana State University, Baton Rouge, Louisiana. Other individuals who provided assistance in data gathering and report preparation were Robert P. Brown, Helen Richardson, and Mary Jo Humke.

The study was monitored by Dr. Richard K. Peddicord for Dr. Robert M. Engler, Manager, Environmental Impacts and Criteria Development Project, EL, WES. The study was under the general supervision of Dr. John Harrison, Chief, EL, WES.

Director of WES during the preparation and publication of this report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.0283	cubic metres
cubic feet per second	0.0283	cubic metres per second
feet	0.3048	metres
feet per second	0.3048	metres per second
degrees fahrenheit	0.555	degrees centigrade
degrees (angle)	0.01745	radians
cubic yards	0.7646	cubic metres
miles	1.6093	kilometres
miles per hour	1.6093	kilometres per hour
inches	2.54	centimetres
square miles	2.58999	square kilometres
cubic inch	16.3871	cubic millimetre
ounces (mass)	28.3495	grams
ounces (fluid)	29.5735	millilitres
tons (short, 2000 lb)	907.1847	kilograms
acres	4046.856	square metres

EFFECTS OF TURBIDITY AND SUSPENDED MATERIAL IN AQUATIC ENVIRONMENTS

Literature Review

PART I: INTRODUCTION

1. Turbidity is a water quality parameter that is routinely measured as part of most fresh, estuarine, and coastal research programs and monitoring surveys. In recent years, more attention has been focused on the possible adverse effects of turbidity and suspended material in aquatic environments. However, there is still a paucity of reliable qualitative and quantitative information on the direct effects of elevated suspended solids concentrations in aquatic environments.

2. This review of the literature on the effects of turbidity and suspended material in aquatic environments is divided into three major areas. Part II includes a discussion of the various definitions, units of measure, and methods of measurement of turbidity and suspended material. Because of the multiplicity of definitions, units of measure, and methods of measurement, comparison of data is difficult. As a result, Huston and Huston (1976) have suggested that current turbidity standards are frequently ambiguous as well as practically and environmentally unrealistic, particularly for dredging.

3. Part III considers the origins of turbidity and suspended material. Each year an enormous volume of suspended material enters the lakes, rivers, and coastal systems of the United States. All waters, whether fresh or salt, contain some solid matter in suspension and may at times contain very high concentrations. Turbidity in water is the result of a number of materials, including clay, silt, finely divided organic and inorganic matter, plankton, and other microscopic organisms. The sources of this turbidity and suspended sediment include a number of both natural processes and human activitites, with two of the more important sources being land erosion and dredging and disposal of dredged material. Curtis et al. (1973) calculated that each year the

rivers and streams of the continental United States (U. S.) carry about 500 million short tons* of sediment into the sea, while the Corps of Engineers (CE) annually dredges about 400 million cu yd of material in the maintenance of over 19,000 miles of navigable waterways (Boyd et al., 1972). Because of the recognized importance of dredging, the need for environmentally compatible dredging and disposal operations is obvious.

4. Part IV considers the effects of turbidity and suspended material in aquatic environments, including water quality, primary productivity, selected groups of invertebrates, and fishes. The effects of a wide variety of particles have been examined, including numerous commercially processed substances as well as natural sediments. Investigations have been conducted in both the laboratory and in the natural environment involving a variety of techniques and methodologies. Obviously all of the above variations contribute to the difficulty of comparing results.

5. From an examination of the literature, it is apparent that there are a number of ways in which turbidity and excessive concentrations of suspended material might affect aquatic organisms. As outlined by the European Inland Fisheries Advisory Commission (EIFAC, 1964), these possibilities are:

- a. Action directly on the organisms which either would kill or reduce growth rate and resistance to disease.
- b. Prevention of the successful development of eggs and/or larvae.
- c. Modification of natural movements and migrations.
- d. Reduction in the abundance of available food.

A complete survey of the literature on these topics is not possible because of the voluminous amount available. Therefore, several recent, comprehensive bibliographies are listed in paragraph 71.

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* A table of factors for converting U. S. units of measure to metric (SI) units of measure is presented on page 13.

PART II: DEFINITIONS, UNITS OF MEASURE, AND METHODS OF MEASUREMENT OF TURBIDITY AND SUSPENDED MATERIAL IN AQUATIC ENVIRONMENTS

6. Human activities such as dredging and filling operations and agricultural, industrial, and municipal effluents are contributing to the increase in turbidity and suspended material. In addition to the aesthetic problems associated with the reduction in water clarity, some aquatic organisms are sensitive to increases in turbidity and suspended material. Turbidity is not a simple parameter, but represents a complex composite of several variables that individually and collectively interfere with the transmission of light through a liquid medium. Confusion regarding the definition and measurement of turbidity has been compounded because of the often indiscriminate and interchangeable use of such terms as transparency, visibility, clarity, opacity, color, and suspended solids. In some of the older literature, the observed results are almost certainly due to siltation rather than turbidity or suspended solids effects, even further "muddying the waters." The following section briefly reviews the definitions, units of measure, and methods of measurement of turbidity and suspended material in aquatic environments. Excellent, more comprehensive discussions may be found in those papers by Hach (1974) and McCluney (1975).

Definitions

7. Several authors, including Austin (1973a,b), Carranza (1973), and McCluney (1975), have thoroughly and critically reviewed the various definitions of turbidity appearing in the literature. The variety of substantially different turbidity definitions is due to the differing needs of investigators in various disciplines and from the convenience of the word turbidity as a catchall term for all water clarity measurements (McCluney, 1975).

8. One of the most widely accepted qualitative definitions of turbidity is that proposed by the American Public Health Association (APHA) (1976). Turbidity is defined as "an expression of the optical property

of a sample that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample". The definition is qualified with the addition of the statement that "attempts to correlate turbidity with the weight concentration of suspended matter are impractical because the size, shape, and refractive index of the particulate materials are important optically but bear little direct relationship to the concentration and specific gravity of the suspended matter". This has been demonstrated by numerous investigators, including Duchrow and Everhart (1971) when they attempted to establish a relationship between turbidity and the concentration of suspended particles specifically for salmon and trout streams. They concluded that too many factors must remain constant before a turbidity measurement may be converted to a corresponding suspended sediment concentration.

9. The recognition of this led Carranza (1973) to include within his definition the statement that turbidity must be defined and measured in a specific manner for each discrete particle system. Similarily, McKee and Wolf (1963) stated that turbidity is not equal to the concentration of suspended solids, but is an expression of only one effect of suspended solids upon the character of the water.

10. Although the APHA definition encompasses a large number of other qualitative definitions found in the literature, several authors (Austin, 1973a; Carranza, 1973; McCluney, 1975) argue that it is inadequate for several reasons: it is not clear whether true extinction (unscattered light) or diffuse extinction (scattered and unscattered light) is involved and secondly, several optical properties rather than a simple optical property are operating.

11. A number of quantitative definitions based on optical and gravimetric principles are also available in the literature. The transmission of light through water is always associated with attentuation due to two processes, absorption and scattering, although some definitions do not apply to the reduction in transparency caused by both (McCluney, 1975). Absorption is the conversion of radiant energy into other forms of energy, including heat and photosynthetic energy. Scattering is produced as a result of discrete particles and may be considered as the

deviation of the incident beam from rectilinear propagation (Jerlov, 1970).

12. Natural waters, because of dissolved light-quenching components, absorb light at a region of the spectrum that differs from that of pure water. The ionic composition of water exerts only a weak influence on light so that salt contribution may be ignored.

13. Suspended particulates are responsible for absorption as well as scattering, with the angular variation of particulate scattering proportional to the nature and size of the particles. In general, absorption predominates in clear lakes and oceanic waters, while scattering is the predominant optical property in rivers and estuaries.

14. The sum of three coefficients (for pure water, dissolved substances, and suspended substances) contribute to the total coefficient of absorption in natural waters--i.e., the remaining intensity of light, having passed through a column of water of some given depth, is a function of the sum of the three coefficients. Because of this, a similar attenuation of light can occur as a result of dissimilar causative factors. The total coefficient of absorption is usually what is implied by limnologists and oceanographers with the use of the terms extinction coefficient, absorption coefficient, and attenuation coefficient.

15. Because there is a problem in relating turbidity to concentrations of suspended material, gravimetric techniques for determining sediment concentration directly from a water sample have been devised, resulting in the proliferation of additional terms. A number of grade-scale systems have been designed to facilitate the description and analysis of the particle size distributions of suspended and bottom sediment samples, including the Wentworth and U. S. Bureau of Soils Systems. The important particle categories in relation to turbidity and suspended material are the colloids (< 0.24 μm), clays (0.24-4.0 μm), silts (4-63 μm), and sands (63-1000 μm).

16. Estimation of the amount of suspended material that a current can transport without appreciable sedimentation is difficult, since it depends on the nature of the particles, water velocity, turbulence, etc. Stokes' law for the free fall of small spheres in a fluid medium states

that the rate of sinking varies directly with the square of the radius (Ruttner, 1963). When applied to particles in the size range between clays and sands, under identical conditions of density and viscosity, a spherical particle of 10 μm in diameter will sink 100 times more slowly, and a similar particle of 1 μm 10,000 times more slowly, than a particle 100 μm in diameter.

Units of Measure

17. The units of turbidity measurement are nearly as varied as the definitions of turbidity. The measurement of turbidity dates back to the work of Whipple and Jackson in 1900 when they formulated a standard suspension fluid using 1000 ppm of suspended silica prepared from fuller's or diatomaceous earth in distilled water (Hach, 1974). This was then diluted to prepare a series of standard suspensions used to calibrate the turbidimeters used in that day, principally the Jackson Candle Turbidimeter. The turbidimeter consisted of a special candle and a glass tube that had been graduated in Jackson Turbidity Units (JTU). The measurement was made by pouring a turbid sample into the tube while observing the candle flame through the sample. The turbidity in JTU's corresponded to the depth of sample in the tube at the point of image extinction.

18. Although a candle turbidimeter is no longer widely used, the scale remains and is the basis for all turbidity measurements in JTU's. In the past, the term "ppm turbidity, silica scale (ss)" was often used in place of JTU's. This is now incorrect, because it has been shown that very fine particles do not scatter or reflect long wavelengths of light--i.e., very fine silica turbidity will not produce a flame image extinction in a Jackson Turbidimeter. These fine particles can be measured by a photo-electric turbidimeter that uses an incandescent lamp as a light source (Hach, 1974). With the general discontinuation of the terms "ppm units" and "silica scale," some authors simply adopted "turbidity units" (TU).

19. In 1926, an excellent alternate standardizing material,

Formazin, was developed (APHA, 1976). The Formazin turbidity standard has a Jackson turbidity value of 4000 units. The mixture can be diluted to prepare direct standards of any value without standardizing the stock suspension with a candle turbidimeter and has a reported repeatability accuracy of ± 1 percent. As a result, a new turbidity unit, the Formazin Turbidity Unit (FTU), and a new turbidity standard have been widely adopted.

20. A new unit, the Nephelometric Turbidity Unit (NTU), has been recently introduced into usage by the APHA (1976). Nephelometric units are based on a Formazin Standard and tie the unit of turbidity measure (the NTU) to the instrumental principle (nephelometry) from which the unit is derived. Nephelometry measures the amount of light reaching a sensor at $90°$, rather than at $180°$, to the incident beam as in most turbidimeters.

21. Because the experimental data examined in this review have not been reported in a standardized format, all values are presented in the units used by the original investigators.

Methods of Measurement

22. The two primary applications of turbidity measurements, as listed by Pickering (1976), are a) biological--as a measure of light penetration and, therefore, depth to which biological activity in green plants will take place and b) sediment--as an indication of the concentration of suspended material.

23. There are numerous instruments available for measuring turbidity. Despite the number of factors affecting its measurement, turbidity has historically been determined by such apparently simple means as the Jackson Candle Turbidimeter, the principles of which were discussed above, and the Secchi disc (McCarthy et al., 1974). Although there are a number of advantages in using the candle turbidimeter (no moving parts, free of electronic component failure, inexpensive), there are also a number of limitations. The light produced by the candle flame is predominately in the yellow-red end of the spectrum. Because very fine

particles do not scatter or reflect these longer wavelengths, the candle turbidimeter is not suitable for use with colloidal suspensions or solutions with turbidity readings below 25 JTU's. The candle turbidimeter is also incapable of measuring black particles, such as charcoal turbidity. The absorption of light is so great in comparison to scattering that the field of view darkens before enough sample can be poured into the tube to reach an image extinction point (Hach, 1974).

24. The Secchi disc is a white, circular disc that is lowered into the water until it just disappears from sight. The measurement of Secchi depth is not strictly a turbidity measurement and yields only approximate information about water clarity. The lack of early specifications for this device and the fact that Secchi depth is subject to a number of extraneous influences (surface waves, atmospheric variations such as haze and clouds, and visual acuity of the observer) makes Secchi depth measurement very subjective and little more than a qualitative estimate of water clarity.

25. The majority of the remaining turbidity measurement techniques may be separated into two predominant classifications: those that involve gravimetric measurements and those that are optical measurements. The latter group may be subdivided into two, though not inclusive, categories: those based on a comparison with standard suspensions of known turbidities and those based on the absolute measurement of some optical quantity.

26. In an attempt to circumvent the problem of relating turbidity to actual concentrations of suspended material, various investigators have used gravimetric techniques to determine sediment concentrations directly from a water sample. Many of the methods are tedious and time consuming. Most techniques involve the filtration of a sample of a known volume through a tared glass fiber filter followed by oven drying at about 105°C and reweighing. Care must be taken to ensure that the sample is well mixed and the maximum volume of water consistent with not clogging the filter is used. The result is a measure of the suspended material in terms of weight/volume units that can be easily and accurately compared.

27. Most investigators use optical turbidity measurement techniques. Rather than discuss each turbidimeter on the market today, since models and design principles change, a general discussion concerning the usefulness, appropriateness, and shortcomings of the two major categories follows.

28. Of the photoelectric instruments based on standard suspensions of known concentrations, the nephelometer enjoys the widest acceptance (Hach, 1974) and has been adopted by the APHA (1976) as the preferred means for measuring turbidity. The nephelometer differs from the transmissometer (absorptometer) in a number of ways. Turbidity particles scatter light and the photocell in a nephelometer measures the light scattered at approximately right angles to the incident beam. Turbidity particles also absorb light, and the photocell in a transmissometer measures the remaining light at 180° in relation to the incident light source. The output signal from a nephelometer is zero at zero turbidity and increases directly with respect to turbidity. Any degree of sensitivity can be obtained by increasing the brightness of the light or by increasing the sensitivity of the photocell system. By contrast, transmissometers measure a negative response as the signal decreases with increasing turbidity and little can be done to obtain a higher sensitivity.

29. The most serious disadvantage of a nephelometer is the matter of stray light. The presence of dirt and bubbles on the walls or windows of the sample cells may produce substantial amounts of scattered light, which may result in erroneously high readings, especially in the lower measurement readings. Thus some investigators recommend against the use of side scattering instruments with wide viewing angles.

30. While the trend has been towards side scattering turbidimeters (nephelometers), frequently a State or Federal agency specifies a turbidity standard in JTU's. Nephelometer units do not correlate well with JTU's. The reason is that angular variation of particulate scattering is proportional to the nature and size of the particles. Black and Hannah (1965) and Simms (1972) noted that for particles less than 0.1 μm the intensity scattered backward is equal to the intensity scattered forward, while the side scattered intensity is half this value. For

particles between 1.0 and 50 μm the forward scatter intensity can be 1000 times the side scattered intensity. Since most of the particles encountered in natural and waste waters fall in the 1.0 to 50 μm range, Simms (1972) maintains that the forward scatter turbidimeters correlate better with these particulate concentrations.

31. Most of the nephelometric turbidimeters are laboratory instruments and are therefore sensitive to changes that occur in the sample from the time it is collected to the time it is measured. These changes may be substantial.

32. The second category of optical turbidimeters, which are those based on the absolute measurement of some optical quantity, includes a number of turbidimeters commonly known as transmissometers. Transmissometers are true extinction meters. The readout is in percent transmittance which can be easily converted into an extinction coefficient. Because the readout is not in units such as JTU's or FTU's, which are specified in some regulations, McCarthy et al. (1974) have criticized this aspect of transmissometers. Transmissometers project a beam of light through a path length of from about 10 cm-1 m to a detector with a narrow angular field of view. The use of a narrow field of view is an effort to minimize the amount of small-angle, singly scattered, and multiply scattered light involved in the measurement (McCluney, 1975). Most transmissometers also contain broadband optical filters to restrict the wavelength range over which the measurement is obtained.

33. Pickering (1976) stated that the application of transmissometers may be advantageous where the role of absorption is of special concern and their use is particularly valuable in investigating the spatial distribution of the total attenuation coefficient.

34. In contrast to the nephelometers, a number of transmissometers may be used in situ. Thus McCluney (1975) believes that transmissometers may be expected to give the most accurate, reliable, and reproducible results and are the preferred type of instrument for water clarity measurements in natural waters. However, a scattering type of instrument comes closest to providing an output proportional to the concentration of the silica scale (McCluney, 1975).

PART III: ORIGINS OF TURBIDITY AND SUSPENDED MATERIAL IN AQUATIC ENVIRONMENTS

35. Turbid waters may be caused by a variety of both natural processes and human activities, including erosion, resuspension of bottom sediments, biological activities, industrial effluents, and dredging. The degree of turbidity produced by each of these factors depends upon the character and concentration of the particles in suspension, as well as the nature of the body of water itself. In lotic environments, the ability to carry suspended sediments is dependent upon both the current velocity and particle size. Critical transportation velocites for particles of various sizes are presented in Table 1. In many environments, turbidity may be the result of a variety of particles of different origin and may vary both spatially and temporally. The following discussion briefly considers several of the sources and variations of turbidity in lakes, rivers, and coastal systems. The sources of turbidity have been the subject of numerous symposia and an extensive amount of literature exists on the subject. Useful bibliographies that deal with the origin and transport of sediments in freshwater habitats are included in the papers by Carranza (1973), Ritter and Brown (1971), Schubel (1971), and the U. S. Environmental Protection Agency (1973a), while the estuarine environment is covered by Guilcher (1967), Freitag (1960), and the Office of Water Resources Research (1973).

Table 1

Critical Transportation Velocities for Particles of Various Sizes (modified from Ruttner 1963 and Twenhofel 1932)

Particle	Mean Particle Diameter, mm	Current Velocity, m/sec
Clay	0.004	0.08
Sand	0.5	0.28
Granule	4.0	0.63
Pebble	7.0	0.86
Gravel	54.0	1.62
Boulder	409.0	4.87

Erosion and Suspension

36. Several authors, including Ellis (1936), Schubel (1971), and Stall (19[illegible]), cite land erosion as the major cause of turbidity in most lakes, rivers, and estuaries in the United States. Erosion is a natural and continuous process that has occurred throughout geologic time. However, since the middle of the last century erosion has been accelerated by activities of man such as farming, logging, surface mining, and construction.

37. Each year, the rivers and streams of the continental United States carry about 500 million short tons of sediment into the sea, with the Mississippi River transporting about 77 percent of this total (Curtis et al., 1973). A summary of drainage areas and annual water and sediment discharge for the Atlantic, Pacific, and Gulf coasts is presented in Table 2.

38. Of the total annual sediment load carried by the rivers in the United States, it is not unusual for a high percentage to be transported during relatively short periods of high-water discharge. During the year of 1 April 1966-31 March 1967, Schubel (1968a) estimated the suspended sediment discharge of the Susquehanna River at Havre de Grace, Maryland, to be about 6.0×10^5 metric tons. Approximately 70 percent of this total, or about 4.2×10^5 metric tons, was discharged during the period of peak river flow in February and March (Schubel, 1968a).

39. Unusually high turbidity may also be associated with catastrophic floods which occur at irregular intervals on the order of decades or centuries. Preliminary estimates indicate that in a 7-day period in June 1972, during and following the passage of Hurricane Agnes, the discharge of sediments from the Susquehanna River exceeded the total mass of sediment discharged during the past decade, and perhaps during the past half century (Anderson et al., 1973). The bulk of the sediment was silt and clay-sized material, but a substantial amount of fine sand was also discharged.

40. Agricultural activity is the major source of eroded sediment. The erosion of croplands is responsible for 50 percent of the sediment

Table 2

Summary of Suspended Sediment Discharge to Oceans from the Conterminous United States (after Curtis et al. 1973)

Water Body	Drainage Area mi^2/km^2	Water Discharge cfs/cms	Water Discharge Percent	Suspended Sediment Discharge Tons Per Year Short/Metric	Suspended Sediment Discharge Percent
Atlantic Ocean	287,166 743,760	359,350 10,180	20.6	14,204,000 12,885,726	2.9
Gulf of Mexico	1,739,200 4,504,528	887,400 25,120	50.8	378,179,000 343,080,207	77.0
Pacific Ocean	632,410 1,637,942	499,065 14,132	28.6	99,066,600 89,872,229	20.1
Total	2,658,776 6,886,230	1,745,815 49,432	100.0	491,449,600 445,838,162	100.0

delivered to streams and lakes (U. S. Environmental Protection Agency, 1973a). Stall (1972) calculated that for typical farm fields in Illinois, soil losses commonly ranged from 5 to 10 tons/acre/year. Such losses, however, can be reduced to tolerable levels by soil conservation measures. As an example, after instituting a soil conservation program, sedimentation was reduced by 73 percent in the city reservoir of Fairfield, Iowa (Stall, 1966).

41. Surface mining activities also contribute to increased levels of turbidity by accelerating erosion rates. Strip mining for coal, which is the principle surface-mined commodity, accounts for about 40 percent of the total (4.5 million) acres of land disturbed by surface mining (Spaulding and Ogden, 1968).

42. Research in Kentucky by Musser (1963) indicated that amounts of sediment eroded from forested areas were increased to 1000 times their former level as a direct result of strip mining. During a 4-yr period, the average annual amount of sediment eroded from spoil banks was 27,000 tons/mile^2, while from control areas it was estimated at only 25 tons/mile^2 (Musser, 1963). Using these figures, Spaulding and Ogden (1968) calculated that 34 million tons of sediment were transported annually from the 800,000 acres of strip-mined lands in Appalachia alone.

43. Other types of surface mining that promote erosion include auger mining (also used routinely for coal), quarrying (for copper, iron, and uranium), dredge mining (recovery of sand and gravel), and hydraulic mining (recovery of sand and gold). Hydraulicking in the Boise River Basin in Idaho produced 128,500 tons of silt in 18 months (Spaulding and Ogden, 1968).

44. Oleszkiewcz and Krenkel (1972) found that the total input of suspended solids by a floating sand and gravel dredge in the Ohio River was very small, compared to the average river load, and ranged from only 0.10 - 1.63 percent of the total.

45. The logging of public and private lands, and associated erosion problems, is also an important source of sediment. Tebo (1955) found that logging roads and skid trails were the major sources of sediment in his study area. Skidding logs down the steep slopes resulted in

a high rate of erosion and an estimated 5.34 ft^3 of soil/linear foot of road surface were eroded from the logging roads themselves over a 2-yr period (Tebo, 1955). Similar increases in sediment load during and following logging operations were reported by Packer (1967), Hall and Lantz (1969), and Youngberg et al. (1971). In an Oregon study, sediment concentrations in adjacent streams 250 times those of streams in uncut areas were not uncommon (Krygier et al., 1971).

46. Urbanization is yet another source for increases in sediment yields to streams, rivers, and lakes. An extensive recent bibliography on the subject has been compiled by Carranza (1973). Scheidt (1967) reported that sediment yields in the Potomac and Patuxent River Basins of Maryland were about 200 tons/$mile^2$/year under natural conditions but increased to a maximum of 121,000 tons/$mile^2$/year in areas where urbanization had converted land to developments. Thompson (1970) reported that a construction site in Detroit, representing only 2 percent of an urban zone, was responsible for more sediment than the remaining 98 percent during the period of construction. The average annual gross erosion rate for the entire Great Lakes Basin is nearly 2 tons/acre/year (Great Lakes Basin Framework Commission, 1972). Erosion from urban construction currently produces about 5 percent of the total erosion in the Basin and projected population and economic growth indicate that this rate will increase to about 10 percent of the gross erosion in the Basin by the year 2020.

47. Vittor (1972) reported that a highway construction site along D'Olive Creek, Alabama, resulted in such substantial increases in sediment load and turbidity that over 12 in. of red clay had accumulated during the 1-yr study.

Resuspension

48. Resuspension of bottom sediments is an important source of turbidity in lakes, bays, and estuaries. Resuspension is usually the result of wave action and currents on fine, unconsolidated sediments (silt and clay) and detritus. Both Chandler (1942) and Langlois (1941) found

that turbidity in Lake Erie rose from an average of 40 ppm to over 200 ppm following disturbance of the bottom by 40 mph winds. Similar results have been reported for numerous other large bodies of water, including several Texas reservoir lakes (Harris and Silvey, 1940), Lake Chautaugua, Illinois (Jackson and Starrett, 1959), Lake Blackwell, Oklahoma (Norton, 1968), Lake Pontchartrain, Louisiana (Stern and Stern, 1969), and Lewis and Clark Lake, South Dakota (Walburg, 1964).

49. Krone (1966), analyzing the pattern of sediment movement in San Francisco Bay, found that sediment entered the Bay predominantly with the higher flows during the winter and spring months. A large portion of the incoming sediment was deposited initially in the shallow areas of the Bay, with smaller portions deposited in channels and around docks, and the remainder passed out to sea. Calm winds in the Bay during winter and spring months alternate with daily onshore breezes during the summertime. Krone (1972) estimated that afternoon winds in excess of 10 mph were capable of resuspending 2200 tons of sediment/day in San Francisco Bay. Such resuspended sediments are carried from shallow parts of the Bay by wind induced and tidal currents to deeper portions of the Bay. During those periods while wave action was in progress, suspended sediment concentrations were as high as 1 g/ℓ (Krone, 1966).

Turbidity Maxima

50. Fresh water-salt water density currents in estuaries have been discussed by numerous individuals, including Conomos and Peterson (1973), Schubel (1968b) and Schultz and Simmons (1957). When estuarine circulation patterns develop in the lower reaches of many rivers, the concentrations of suspended matter often are considerably higher than those in the source river or further seaward in the estuary, producing what are known as turbidity maxima (Postma, 1967). Although the existence of turbidity maxima is usually due to hydrodynamic conditions, their formation has also been attributed to the flocculation and deflocculation of river-borne sediment (Schubel, 1968c). A recent discussion on the formation of turbidity maxima and the fate of suspended material in

estuaries may be found in Krone (1976). A sediment particle carried downstream with the river may sink into the denser, high salinity water beneath the halocline. Since net water movement in this layer is upstream, the particle will move back upstream. The particle is carried back into the upper layer by vertical mixing, then seaward again. Repetition of this cycle results in high concentrations of suspended matter. Nelson (1960) measured the turbidity maximum at the mouth of the Pamunkey River, Virginia, and recorded a suspended sediment concentration of 100 mg/ℓ, while the concentrations upstream and seaward were about 30 mg/ℓ and 15 mg/ℓ, respectively.

Turbidity Currents

51. High concentrations of suspended material under the influence of gravity may produce naturally occurring topographically controlled turbidity or density currents which are capable of flowing great distances along the bottom of lakes (Baumgartner et al., 1973; Hutchinson, 1975; Plumb, 1973), and down the continental slope and onto abyssal plains of the open ocean (Gunnerson and Emery, 1962; Kuenen, 1950; Shepard, 1963; Stanley et al., 1972). Similar density layers have also been observed where dredged material slurry is being disposed at designated open water disposal sites (May, 1973). The initial movement of the sediment itself can be the result of dredging activity or may occur naturally due to the discharge of fluvial deposits into a large body of water, or may accompany the sliding of an unconsolidated mass of sediment down a slope. Most direct observations of turbidity currents have been confined to lakes where the highly turbid river water entering the lake is of a higher density than the lake water. Plumb (1973) found the velocity of a turbidity current (composed of ore tailings) in Lake Superior to be 1-2 fps.

Biological Sources

52. Biological products and activities that contribute significantly to the turbidity of natural waters include plankton blooms, the

production of organic detritus, and the feeding activities of certain fishes. A brief survey of these sources follows.

53. Planktonic organisms are usually present to some extent in natural waters. Because most species are microscopic and sparsely distributed, they usually are not a directly observable component of the aquatic environment. Bay far the most obvious and often most numerous forms of phytoplankton are the diatoms. Whereas most planktonic diatoms are nonmotile, the second major constituent of the phytoplankton, the dinoflagellates, possess the power of movement. It is this latter group that is responsible for what are commonly referred to as "red tides." Most of the remaining forms of plankton comprise the zooplankton, which feeds on phytoplankton, bacteria, and other suspended particles.

54. Under favorable circumstances, the phytoplankton forms may reproduce so rapidly in lakes or coastal waters that they become highly concentrated and the water becomes moderately to very turbid. These rapid, sometimes explosive population increases are known as "blooms" and often impart a noticeable brownish, reddish, or yellowish color to the water. For diatoms, excessively rich concentrations may contain 5-6 cells/mm^3 while for dinoflagellates the number may reach 50 cells/mm^3 in red tide outbreaks (Raymont, 1963).

55. The precise causes of red tides and other plankton blooms are often a matter of speculation. Ingle and Martin (1971), Pomeroy et al. (1956), and Rounsefell and Dragovich (1966) have tried to correlate red tides with a number of factors for predictive purposes. It is clear that the factors affecting primary production include light, temperature, inorganic nutrients, and organic micronutrients (i.e., vitamins), and that productivity varies from one body of water to another. The effects of turbidity on plankton blooms and the impact of plankton blooms as a source of turbidity are discussed in a subsequent section of this report.

56. In many estuaries and coastal areas, organic detritus in various stages of decomposition represents an important source of turbidity. The major natural source of organic detritus in coastal marshes and estuaries is vascular plants (Odum et al., 1973). Odum and de la Cruz (1967) calculated that about 90 percent of the total suspended

matter, or seston, in a Georgia estuary was detritus. Sherk (1972) reported that of the suspended sediments entering the upper reaches of the Chesapeake Bay, the organic fraction was 26 percent. The organic matter in surface waters of the Atlantic Continental margin from Cape Cod to the Florida Keys varied from 24 to 90 percent of the total suspended matter with only a small part consisting of recognizable organisms (Manheim et al., 1970).

57. The resuspension of fine-grained bottom deposits and the destruction of rooted aquatic vegetation by the foraging of fish, particularly carp, is also a source of turbidity in shallow freshwater lakes and impoundments (Cahn, 1929; Jackson and Starrett, 1959; Summerfelt et al., 1970). Carp, catfish, buffalo, suckers, and other rough fish species forage along the bottom in search of benthic organisms, detritus, and other foods. This action causes extensive stirring and mixing of the bottom sediments. The turbidity of the water increases directly as a result of this stirring process and indirectly as a result of the destruction of the rooted vegetation that stabilizes the bottom sediments. Following the introduction of carp into a small lake in Wisconsin, Cahn (1929) reported the extensive elimination of both rooted vegetation and native game fishes and a significant increase in turbidity. Summerfelt et al. (1970) reported similar findings in several Oklahoma reservoirs. However, in another study, Wright (1954) found no evidence that carp were affecting the productivity of an Ohio reservoir by eliminating vegetation or making the water turbid.

Waste Discharges

58. The continuous discharge of wastes into rivers, lakes, and coastal waters is another important cause of increased turbidity. The papers and contained bibliographies by the Council on Environmental Quality (1970) and National Marine Fisheries Service (1972) are helpful overviews of this subject. About 48 million tons of waste was dumped at sea in 1968, including dredged material, industrial waste, sewage sludge, construction debris, and solid waste (Council on Environmental Quality,

1970). The quantities for each category are summarized by coastal region in Table 3. Because dredged material accounts for 80 percent by weight of all ocean dumping, it has drawn special consideration.

59. The Corps of Engineers, in the development and maintenance of the Nation's waterways, is responsible for dredging more than 400,000,000 yd^3 of material a year (Huston and Huston, 1976). As a result, a dredged material research program has been conducted by the Environmental Laboratory, WES. A number of research studies have been conducted to consider criteria for the disposal of dredged material (Boyd et al., 1972; Lee and Plumb, 1974; Lee et al., 1975) and techniques for the reduction of turbidity associated with dredging operations (Huston and Huston, 1976), as well as a host of additional problems. Saucier et al. (1976) contains an overview of the program and a comprehensive list of federally funded research reports published on the subject. In addition, numerous other dredged material disposal studies, seminars, and symposia have been sponsored by related agencies and the resultant literature is also extensive.

60. Significant increases in turbidity have been attributed to dredging operations and to the open-water discharge of dredged material (O'Neal and Sceva, 1971a). Dredged material consists of sediments containing various concentrations of sand, silt, clay, and municipal and industrial sludges. Thus increases in turbidity from dredging activities may potentially be accompanied by the depletion of dissolved oxygen and the release of pollutants and nutrients. The extent of the environmental modifications depends upon the size, duration, and frequency of recurrences of the project; the quantity and nature of the sediment moved; the methods of excavation, transport, and disposal; and the rates of circulation and mixing of the receiving waters. Some of the dredged material deposited in open waters remains in a semisolid state and sinks immediately to the bottom where the material remains more or less permanently at rest. This is most likely the case when the excavated material is coarse sand, gravel, or consolidated fine-grained material excavated by clamshell dredge and when the waters in the disposal area are calm. When the sediment to be dredged is composed of unconsolidated

Table 3

Ocean Disposal of Waste Material by Coastal Region

(from Council on Environmental Quality, 1970)

Waste Type	Quantity, metric tons Atlantic	Gulf	Pacific	Total	Percent of Total
Dredged Material	15,808,000	15,300,000	7,320,000	38,428,000	80
Industrial Wastes	3,013,200	696,000	981,300	4,690,500	10
Sewage Sludge	4,477,000	0	0	4,477,000	9
Construction Debris	574,000	0	0	574,000	<1
Solid Wastes	0	0	26,000	26,000	<1
Explosives	15,200	0	0	15,200	<1
Total	23,887,400	15,996,000	8,327,300	48,210,700	100

silt and clay, or when the disposal area is frequently subjected to wave action or strong currents, a portion of the dredged material may be placed in suspension. That fraction of the dredged material that settles to the bottom immediately after discharge may itself be subject to resuspension. A very wide range of concentrations of suspended solids from dredging operations have been reported, the differences reflecting the variables discussed above.

Other Causes of Turbidity

61. Several other activities of man also cause or increase turbidity. The bottom sediments in shallow bays are particularly susceptible to resuspension by boat traffic and other disturbances. Mackin (1962) reported that shrimp trawlers dragging nets in Barataria Bay, Louisiana, produced turbidities ranging from 71 to 97 ppm in an area where the natural turbidity range was 17-29 ppm. The turbidities produced by the shrimp trawlers were not excessive, but they were greater than those produced by a nearby hydraulic pipeline dredging operation at distances of 300 ft from the discharge pipe (Mackin, 1962).

62. Undoubtedly shipping and fishing operations in other areas also contribute to increases in turbidity. In a study of the relationship between benthic infauna and maintenance dredging in Coos Bay, Oregon, McCauley et al. (1977) suggested that an area subjected to maintenance dredging would also be subject to frequent disturbances by ship movements and other harbor activities. They concluded that the infauna became adapted to these activities. Thus, because maintenance dredging is a usual event, it should not be expected to have catastrophic effects (McCauley et al., 1977).

Turbidity-Reducing Processes

63. There are a variety of natural physical, chemical, and biological processes that tend to reduce the turbidity in natural waters. The major physical process is settling. The settling of single, discrete

particles in calm waters varies in accordance with Stokes's Law, as discussed previously. Gravitational settling depends primarily on grain size and immersed density--i.e., the difference between the density of a suspended particle and the density of the suspending medium. Because the difference in density between organic matter and water is very small, organic particles settle much slower than inorganic particles of comparable size. Shape also has an important effect on the settling velocity of very small particles. Thus, fine spines, bristles, hairs, or setae on planktonic organisms may greatly reduce their settling velocity.

64. The agglomeration of small particles tends to increase the rate at which they settle toward the bottom. Schubel and Kana (1972) analyzed a surface water sample from the Chesapeake Bay's turbidity maximum and determined that while primary particles accounted for more than 70 percent of the total number of particles, they accounted for only about 2 percent of the total volume of particles. Agglomerates composed of more than 3 units, while making up only about 11 percent of the total number of particles, made up nearly 97 percent of the total sediment volume. Clearly, in this sample the bulk of the sample volume was made up of the larger composite particles. The agglomeration of fine suspended particles may be accomplished in a number of ways, as demonstrated by Schubel and Kana (1972), including the activities of zooplankton (copepods), bacterial activity, and flocculation.

65. A large number of organisms filter suspended particles from the water column. Subsequently the undigested material may be eliminated in the form of fecal pellets, which, because of their large size and density, settle rapidly to the bottom. The majority of filter feeders are invertebrates (tube-dwelling worms, bivalve molluscs, plankton), but there are a number of vertebrates that also utilize this method of feeding (certain fishes and aquatic mammals).

66. Lund (1957a,b) discussed the ability of oysters to remove suspended silt and the significance for sedimentation geology. Laboratory experiments showed that under laboratory conditions normal oysters deposited by self-silting about 8 times the volume of sediment deposited by gravity alone under exactly the same conditions of sedimentary load,

velocity, and volume flow of seawater. Calculations based upon these experiments showed that the volume of self-silt produced by a single continuous layer of oysters in 11 days, on an area of one acre, would amount in volume to 35.9 yd^3. The equivalent dry weight would be 8.36 tons.

67. Finally, heavy vegetative cover helps to decrease turbulence near the bottom as well as stabilize the bottom sediments and retard their resuspension.

PART IV: EFFECTS OF TURBIDITY AND SUSPENDED MATERIAL IN AQUATIC ENVIRONMENTS

68. This section contains a review of the literature concerning the effects of turbidity and suspended materials in fluvial, lacustrine, estuarine, and coastal marine environments. The literature dealing with oceanic waters has not been included and chemical pollution is treated only as it is influenced by the presence of suspended particulates. Mixed effluents from various sources increase the turbidity of the receiving water, but it is difficult to distinguish between the effect of attenuation of light due to the suspended particles and the direct effect of the particles in suspension on the growth and physiology of aquatic organisms (U. S. EPA, 1973c). Synergistic and antagonistic effects associated with these complex wastes also complicate the interpretation of the data. The response of organisms to suspended substances is difficult to determine and may not be due to the actual concentration of suspended solids, but to the number of particles in suspension, their densities, size distribution, shape, mineralogy, sorptive properties, or presence of organic matter and its form (Sherk, 1972). Sherk (1971) also pointed out that each site has its own inherent physical, chemical, and biological limits beyond which significant effects will occur. Therefore Sherk (1972) felt that an assessment of the following should be considered prior to the initiation of any dredging project: a) the types of particles to be resuspended and transported, where they will settle, and the resulting substratum changes; b) the biological activity of the water column and the sediment-water interface; c) the beneficial or detrimental effects of the resuspension of chemicals sorbed or otherwise associated with the particles; and d) the relationships between properties of the suspended load and the transitory and resident species in the area.

69. Cairns (1968), aware of the variation of the biological effects of suspended solids as outlined above, listed the following mechanisms of interaction:

<u>a</u>. Mechanical or abrasive action.

b. Reduction of light penetration.

c. Availability as a growth surface for bacteria and fungi.

d. Adsorption and absorption of chemicals.

70. In a previous section, the distinction was made between suspended materials and siltation, although in the older literature the two may have been used synonymously. Siltation is not extensively discussed; however, frequently its effects are not distinguished in the literature from those of suspended particulates. The recent literature clearly defines turbidity in terms of the modification of the optical characteristics of a body of water due, in this case, to the presence of suspended substances (Pickering, 1976). To include the effects of siltation in this literature review might serve to perpetuate the misconception that turbidity or suspended particulate concentration and siltation are somehow synonymous.

71. The ecological significance of turbidity has been discussed in the literature for several decades. Many of the initial studies dealt with the erosion of agricultural areas and the transport and deposition of these sediments. Gradually the emphasis has shifted toward other sources of turbidity, including dredging, strip mining, and the discharge of industrial and municipal wastes. Simultaneously the volume of literature on the subject has increased substantially, and is continuing to expand. Thus it is possible to introduce only a portion of what is available on each subject. Three recent publications warrant special attention because of their bibliographies, although all three are primarily dredged material studies. May (1973) summarized most of the literature for the period 1938-1972, while Lee and Plumb (1974) and Lee et al. (1975) covered that period and the period up to 1975. When broken down into the following categories, the most helpful bibliographies on the environmental effects of turbidity in aquatic environments may be found in those papers by:

a. General effects of turbidity and suspended materials - Carranza (1973), Lauff (1967), National Marine Fisheries Service (1972), Peddicord et al. (1975), Schubel (1968b), Sherk (1971, 1972), Sherk and Cronin (1970), Tarzwell (1957), US EPA (1973c), Wilber (1971), and Youngberg et al. (1971).

b. Effects of turbidity and suspended material on water quality - O'Neal and Sceva (1971a), Plumb (1973), Stall (1972), and Windom (1973).

c. Effects of turbidity and suspended material on primary productivity - Keefe (1972) and Sherk et al. (1976).

d. Effects of turbidity and suspended material on invertebrates - Chutter (1969), Hart and Fuller (1974), Loosanoff (1961), and Peddicord et al. (1975).

e. Effects of turbidity and suspended material on fishes - Koski (1972), Peddicord et al. (1975), Plumb (1973), Schubel and Wang (1973), Sherk et al. (1972, 1974).

72. The following discussion considers the effects of turbidity and suspended material on water quality, primary production, selected groups of invertebrates, and fishes.

Water Quality

73. When materials enter an aquatic environment, whether they are of natural origin or are the waste products of man's activity, a number of complex reactions may result. Addition of wastes or byproducts may support life, although it can also result in either overfertilization and overpopulation, or tend to be toxic to living organisms (Richards, 1969). Although still poorly understood, there is increasing evidence that a number of different reactions, including sorption, precipitation, flocculation, and aggregation reactions, are of ecological significance in many aquatic systems (Carritt and Goodgal, 1954; Hood, 1969; Morgan and Pomeroy, 1969; Richards, 1969; Schubel and Kana, 1972).

74. A sorption reaction (i.e., any reaction between a solid and a dissolved substance) may be one of two types: a) adsorption - a surface phenomenon that results in the greater accumulation of some environmental constituent on the solid surface than exists at some distance from the surface; and b) adsorption - the solid takes up a portion of the solution much as a sponge takes up water (Carritt and Goodgal, 1954). Either process may be readily or only slightly reversible-- i.e., undergo desorption. Carritt and Goodgal (1954) suggested that sorption reactions could provide a mechanism by which dissolved substances might be

removed from turbid freshwaters and then transported to and released in estuaries where fresh and salt water mix. Their conclusions are based upon a study of a phosphate sorption complex in Chesapeake Bay. The phosphate-solid sorption complex was formed under the low salinity, low pH, high turbidity regime in the fresh river waters. Upon reaching the estuary, in an environment of higher salinity and pH, the adsorbed layer of phosphates carried by the solids was released, making it available to phytoplankton during photosynthesis. Although attempts were made to measure the effect of particle size and mineral composition on the sorptive properties of the solids, the measurements were inconclusive (Carritt and Goodgal, 1954). Ruttner (1963) studied the sorptive properties of solid particles and noted that a large number of substances may function as adsorbents. Clay particles play the dominant role, but humus colloids, polymorphic inorganic and organic complexes, and surfaces and integuments of living and dead organisms are also important (Ruttner, 1963). Weiss (1951) suggested that the removal of bacteria (*E. coli*) from natural, turbid waters demonstrated a sorption reaction with the suspended solids. These reactions emphasize the importance of suspended solids and bottom sediments as ecological factors in aquatic environments.

75. Precipitation, flocculation, and aggregation reactions also participate in determining the amount and types of materials that will be adsorbed from a body of water by particulate matter (Richards, 1969). The above reactions function in the adsorption, transportation, and desorption of heavy and trace metals, pesticides, and nutrients, the importance and levels of which are increasing in fresh and estuarine waters. The following review briefly considers the effects of these and other constituents on the water quality of aquatic environments. As will become apparent, results are often contradictory.

Metals

76. Metals in proper concentrations are known to be essential in the physiology of all living organisms. However, excessive concentrations can be toxic. Of the approximately two dozen metals known to be harmful in large concentrations, mercury (Hg), arsenic (As), lead (Pb),

chromium (Cr), Nickel (Ni), Zinc (Zn), and copper (Cu) are especially harmful to man (US EPA, 1973c). Recent extensive bibliographies on the subject have been compiled by the European Inland Fisheries Advisory Commission (1964), Friberg et al. (1971), Lee and Plumb (1974), Lee et al. (1975), Plumb (1973), US EPA (1973b), and Young (1971).

77. Sources for the metals present in freshwater and salt water environments are natural weathering of soils, agriculture and mining activities, and industrial and municipal wastes discharges. The metals are then transported in solute and particulate form by streams, rivers, and coastal currents. Almost without exception, studies concerned with the toxicity of soluble materials to aquatic organisms, particularly fish, have been conducted with experimental waters that usually contain little or no suspended solids (Brungs and Bailey, 1966).

78. Wallen et al. (1957) were among the first investigators to use highly turbid water when testing the toxicity of 86 organic and inorganic chemicals to the mosquito fish, *Gambusia affinis.* The lack of nonturbid control and determination of suspended solids concentrations, however, limits the value of this study.

79. In a more recent study, Gustafson (1972) subjected the estuarine clam, *Mya arenaria*, to a number of clay and toxic metal sorption complexes to determine if the clams were able to remove the metals from the sediments. The turbidity regimes averaged 1000 JTU's over a 10-day period; the normal background level at the site of collection was only 50 JTU's. While exposed to such extreme turbidities, the bivalves ceased feeding after 5 days and the results became ambiguous. In the same study, Gustafson (1972) tested the permanence of adsorption of various toxic metals to clays when subjected to vigorous agitation, as would occur during the resuspension of bottom sediments. Agitation increased the adsorption of metals onto the clay, removing from 69.8 percent (Cu) to 97.4 percent (Hg) of the metals from solution. Gustafson (1972), questioning his own experimental design in both studies, suggested that further work was needed.

80. Bothner and Carpenter (1973) investigated sorption-desorption reactions of mercury with suspended matter in the Columbia River,

Washington and Oregon. Natural Columbia River water was spiked with two Hg-labelled radioactive species (mercuric nitrate and methyl mercury chloride) to follow the reactions of the two species with the suspended matter during exposure to river water and seawater. Between 50 and 75 percent of the radioactive species became associated with the particulates in the river water. While at least one half of each of the forms was fairly easily desorbed by filtered river water of lower total mercury content, subsequent washes with seawater removed little additional mercury from the particulates (Bothner and Carpenter, 1973). In a similar study, de Groot et al. (1971) stated that 60 percent of the mercury was desorbed from the sediments after the transition from fresh water to salt water. Although Feick et al. (1972) have also shown the loss of mercury from highly contaminated sediments to salt solutions, Bothner and Carpenter (1973) present several plausible explanations for the differences, such as sampling methods, the nature of the organic and inorganic load which could be substantially different with regard to their affinity for mercury, and the rates of desorption in the laboratory versus those in nature.

81. Few studies are available dealing with the release of metals from dredged material. Yeaple et al. (1972) added 100-185 ppm mercury, as $HgCl_2$, to sediments in aquaria and simulated dredging operations by stirring the water. They found that the mercury concentration in the water increased following agitation and stated that some mercury would undoubtedly be released during a dredging operation. However, it takes months for metals introduced this way to "age" into the sediments in the natural way. May (1973), working in an Alabama estuary, observed very little change in the levels of dissolved heavy metals as a result of channel dredging and dredged material disposal.

82. Saila et al. (1972) studied the chemistry of trace metals in the sediment that was to be dredged from Rhode Island Sound. Metals were found in the sediment and dredged material in the disposal area, but not in the overlying water.

83. Windom (1972, 1973) studied the effects of dredging on water quality in several estuaries of the Southeastern United States.

Monitoring the dispersion of sediments after dredging, he noted an initial increase in the concentrations of soluble iron, copper, and lead above ambient levels, followed by a decrease. Several days later, the concentrations returned to ambient levels or higher. Windom (1973) suggested that the changes of the above metals were related to the iron cycle. The reduced iron in the bottom sediments, after being resuspended through dredging, was oxidized in the water, forming iron hydroxide. Following sorption with the suspended sediment, the iron hydroxide settled to the bottom carrying other metals with it. Subsequent reduction in the bottom sediments desorbed the other metals and ambient levels returned. Unlike the other metals, mercury levels did not follow the same pattern. In his earlier study, Windom (1972) attributed the elevated mercury level to a release of volatile mercury compounds, while in the second study (Windom, 1973), the mercury level remained only slightly above ambient. Windom (1972) concluded that in "natural and relatively unpolluted areas," dredging has no significant effect on water quality and that the dredging of polluted sediments does not necessarily impair water quality in estuarine environments.

84. In two related studies, Jernelöv and Åsell (1973) and Jernelöv and Lann (1973) studied the effectiveness and feasibility of sedimentation and chemical precipitation for removing mercury from contaminated water. The contaminated sediments from Lake Trummen, Sweden, were pumped into a sedimentation pond using an hydraulic dredge. After addition of aluminum sulfate to the water from the first sedimentation pond, the precipitated water was transferred to a second pond. Following flocculation in the second pond, the water was returned to the lake. Before and during the first dredging operation, the background mercury concentration in the lake water ranged from 0.05 to 0.15 μg/ℓ, while the mean concentration in the first sedimentation pond was 0.6 μg/ℓ. After settling and prior to precipitation, the mean mercury concentration had already dropped to 0.1 μg/ℓ and the concentration remained at this level even after the water had been returned to the lake. Thus the first sedimentation process was effective in returning the mercury concentration to its background level. An additional decrease in the

mercury concentration of the drying dredged material was noted after one month. Upon exposure to air, there was rapid formation of volatile dimethylmercury (Jernelöv and Åsell, 1973; Jernelöv and Lann, 1973).

Pesticides

85. The use of various pesticides is increasing on a worldwide basis and not until recently has the environmental impact of pesticides received adequate attention. Not only are such pesticides as DDT (dichlorodiphenyltrichlorothane), chlordane, aldrin, dieldrin, and endrin toxic to many terrestrial and aquatic organisms, but most are slowly degraded by the environment. Because of their high lipid solubility, these compounds also tend to accumulate in both plant and animal tissues at concentrations up to several thousand times above background levels. Thus the highest concentrations are often found among organisms occupying the upper trophic levels because of the biological magnification of many pesticides.

86. The sources of pesticide contamination include direct spraying, spray drift, direct dosing of sewage, industrial wastes, and agricultural runoff. The removal of pesticides from an aquatic environment may occur by one or more of several different processes. Chemical reactions and absorption and inactivation by colloidal material are important in affecting the duration of toxicity. Degradation by microorganisms is also a preliminary step in the cycling of pesticides.

87. The organic content of a sediment could affect its ability to sorb and desorb pesticides. The nature of the particle may determine the pesticides with which it will become associated. It is well known that detritus, which serves as a food source for zooplankton, plays an important role in the transfer of pesticides in the food chain (Hood, 1969).

88. Odum et al. (1969) investigated the relationship between DDT residues and detritus particles and the availability of these residues and detritus particles to the fiddler, *Uca pugnax*. Those detritus particles between 500 and 1000 μm in diameter contained the highest DDT concentrations. This was also the preferred food particle size range of the crabs. After feeding on the contaminated detritus for 10 days,

the fiddler crab had concentrated the DDT residues by a factor of three.

89. Several additional studies have also shown that the organic content of a sediment affects its sorption-desorption characteristics. Lotse et al. (1968) demonstrated a positive correlation between lindane sorption capacity and the organic content of lake sediments. Rowe et al. (1970) also reported that dieldrin and endrin sorption was initially higher in sediments containing organics. After one week, however, no distinction could be made between the quantities sorbed by organic and inorganic sediments. Wang et al. (1972), however, found that the partial removal of organic material, by hexane extraction, from a lake sediment increased the sorption capacity of the sediment for parathion.

90. An analysis of soluble endrin concentration versus weight of suspended sediments in representative samples of Mississippi River water was the basis of a comparison by the FWPCA (1969). Results suggested that soluble endrin concentrations have little relationship to the weight of suspended sediments in river water. Considering the solubility of endrin in water and the range of endrin concentration encountered in river water, it is also possible for endrin to be unrelated to other particulate matter in river water (FWPCA, 1969).

91. As indicated earlier, the clay mineral content is one of the most important inorganic constituents of a sediment. Lotse et al. (1969) reported a positive correlation between the concentration of DDT in the sediment and the amount of fine material in river sediments and Routh (1972) reported the same correlation with lindane sorption by clay lake sediments.

92. Brungs and Bailey (1966) investigated the toxicity of endrin to the fathead minnow, *Pimephales promelas*, in the presence of suspensions of several materials, including montmorillonite clay and activated carbon. Their results indicated that the potential toxicity of endrin in solution was greatly reduced only in the presence of activated carbon to which 95 percent of the endrin became adsorbed. Therefore the condition of endrin when it enters an aquatic environment is an important factor in determining its availability and its potential toxicity to fish. The type of clay mineral present is then of obvious importance

and Lee et al. (1975) discuss the effectiveness of several clays for sorbing various pesticides.

93. The aquatic disposal of dredged material containing soluble pesticides can also be accompanied by the sorption of the pesticides by algae and bacteria. Leshniowsky et al. (1970a,b) reported that bacterial floc is able to sorb aldrin from solution with the same efficiency as natural sediments. Similarly, Hill and McCarty (1967) and King et al. (1969) determined that algae are 10 to 100 times more efficient in the sorption of chlorinated hydrocarbon pesticides than either bentonite clay or natural lake sediment. May (1973), however, found that pesticides were not released during dredging or dredged material disposal operations.

Nutrients

94. While most of the studies on the effects of dredging on water quality have dealt with turbidity, few individuals have investigated the effects of nutrient exchange with suspended sediments on water quality.

95. The release of nutrients can have both beneficial and detrimental effects in an aquatic environment. Nitrogen and phosphorus are the most important plant nutrients (Lee, 1970b) and are available from a number of sources, including domestic and industrial waste waters, urban and agricultural drainage, and natural sources (sediments, ground water, nitrogen fixation). The problem of nutrient uptake and release by suspended materials and bottom sediments has been reviewed by Hood (1969), Lee and Plumb (1974), Lee et al. (1975), May (1973), and Sherk (1971).

96. The results of Carritt and Goodgal (1954) involving the sorption reactions of phosphorus and the ecological implications were discussed previously in the introduction to this section.

97. The beneficial effects of silt as a fertilizer are discussed by Golzé (1950). The periodic overflowing of rivers, such as the Mississippi and Missouri, have long been a source of nutrients to the flooded lands. Only on relatively silt-free rivers like the Columbia is the fertilizing feature not evident and in these areas affected

farmers have been forced to increase their use of commercial fertilizers (Golzé, 1950).

98. Ingle (1952) stated that "oysters fattened quickly in finely particulate and suspended material." In a related study, Ingle et al. (1955) found that nutrient compounds (phosphate, nitrogen, fats, and carbohydrates) were released into the water column from bottom muds resuspended by dredging activities. Biggs (1968) measured the total phosphorus and nitrogen concentrations near a dredge discharge pipe and recorded short-lived concentration increases of 1000 and 50 times greater, respectively, than background levels. May (1973), O'Neal and Sceva (1971b), and Windom (1972, 1973) detected no significant changes in water quality at disposal sites while Martin and Yentsch (1973) could not attribute the changes in nutrient concentrations to either natural fluctuations or dredging. To date, studies on this aspect of water quality are not conclusive.

99. Gahler (1969) demonstrated that sediments could be a source of nutrients by showing that algae growth in aquaria with sediment bottoms was better than that of the controls. In a related experiment, algae growth was noted in aquaria containing distilled water and a suspension of eutrophic lake sediments.

100. Lee (1970a) attributes the release of aquatic plant nutrients, especially nitrogen and phosphorus, to the mixing of sediments with water. Under natural conditions, when mixing is slight, the release of nutrients is small. However, during dredging operations and dredged material disposal, quantities sufficient to cause local algae blooms can be released (Lee, 1970a). Lee (1970a) also determined that the sediment mixing zone extended from 5 to 10 cm below the sediment-water interface. The depth of sediments actively taking part in the exchange is a function of both the composition of the sediment and the mixing energy (Lee et al., 1975).

101. Most investigators studying sediment exchange of nutrients, including Austin and Lee (1973), Gahler (1969), Pomeroy et al. (1965), and Zicker et al. (1956), agree that the mixing of sediments and resultant suspension accelerates the exchange process. Zicker et al. (1956)

attributed the accelerated exchange process to the increased surface area. Numerous physical mechanisms provide the energy necessary to agitate the bottom sediments. Ruttner (1963) suggested wind-induced currents, seiches, and mixing from biological activity, while Lee (1970a) also proposed hydrodynamics. In a field study, Gahler (1969) observed large concentrations of the benthic algae, *Oscillatoria*, floating toward the surface with sediment particles settling beneath the ascending mass. Total phosphorus concentrations in that area were 12 times higher than in adjacent areas.

102. Biological processes also function in the sorption and desorption of nutrients by sediments, although their relative importance is still subject to debate (Lee et al., 1975). Several mechanisms associated with the benthos include the metabolic activities of protozoans (Hooper and Elliot, 1953) and bacterial activity (Livingston and Boykin, 1962). Phosphorus exchange also occurs in the water column through the activities of bacteria and algae (Hayes and Phillips, 1959).

Oxygen demand

103. Reductions in the dissolved oxygen content in aquatic habitats have been commonly associated with and attributed to the occurrence of high concentrations of particulate matter. The oxygen demand of completely suspended dredged materials has not been as intensively studied as has the oxygen demand of sediments in their natural state (Lee et al., 1975).

104. Brown and Clark (1968) were two of the earliest investigators to study closely the reduction in dissolved oxygen levels following resuspension of bottom sediments by dredging. The study sites were located in several tidal bays between Staten Island, New York, and the New Jersey shoreline. The bays were subject to both continuous dredging and accumulations of waste discharges, the latter covering the bottom with a black, soft, oily silt. Dissolved oxygen levels at the dredging sites were 16-83 percent lower than during nondredging periods at the same sites, although because of the nature and concentration of the sediments, these results may not be representative of most dredging and disposal sites.

105. Berg (1970) studied the oxygen uptake in resuspended sediments and determined that total suspension through agitation can increase the rate of uptake by a factor of 10 or more over the rate of uptake in stable sediments. Temperature was the only other initial variable that affected the rate of uptake, while the total concentration of volatile solids, temperature, and the nature of the water, as well as mixing, all influenced the cumulative uptake of oxygen. Reynolds et al. (1973) obtained similar results. They found that completely suspended sediments in the Houston Ship Channel had an oxygen demand of from 15 to 17 times greater than that of quiescent sediments.

106. In a study dealing with the effects of dredging and dredged material disposal on fish in San Francisco and San Pablo Bays, California, a reduction in dissolved oxygen concentration was recorded during disposal operations (US Fish and Wildlife Service, 1970). Water samples taken near the bottom at a site near the dredged material release showed a dissolved oxygen content of 0.1 ppm and a turbidity level of 2000 JTU's. Both dissolved oxygen and turbidity levels returned to normal (7- to 8-ppm dissolved oxygen) rapidly following disposal. The same results were obtained in the laboratory when sediments were introduced into aquaria. The oxygen sag was believed caused either by the adsorption of oxygen molecules onto silt particles or oxygen uptake by organic acids.

107. O'Neal and Sceva (1971a,b) and Slotta et al. (1973), working in the Pacific Northwest, also found that the depression of dissolved oxygen levels and the release of turbidity-producing and toxic materials were the primary water quality problems associated with dredging in areas where the sediments contained large quantities of wood pulp.

108. The studies cited above consistently presented evidence indicating substantial decreases in dissolved oxygen levels related to dredging, but did not discuss the spatial extent or time duration of the decrease. However, the recent observation of Lee et al. (1975), May (1973), and the U. S. Army Engineer District, San Francisco (1973), may be more representative. May (1973), working in estuaries in Mobile Bay, Alabama, reported that dissolved oxygen was not significantly

altered by dredging except in the mud flow. Lee et al. (1975) also concluded that the amount of dissolved oxygen depletion in the water column was minimal and quite transitory. In the San Francisco District (1973) report, field monitoring of 14 releases of freshly dredged sediments revealed brief depressions of oxygen content of the receiving water. Depressions to levels of 50-70 percent of prevailing dissolved oxygen and lasting up to 3-4 minutes were repeatedly measured. These conditions were found only near the bay bottom near the point of release. In all three studies, it was concluded that any oxygen depletion that did occur usually disappeared within a few minutes as a result of rapid mixing of dredging and disposal site water with surrounding waters. Normally, the water column should remain aerobic with at least several mg/ℓ of oxygen present (Lee et al., 1975).

109. Berner (1951) suggested a correlation between low dissolved oxygen levels and high turbidity levels in the lower Missouri River. Oxygen content varied from 95 percent of saturation in clear water (average turbidity of 1700 ppm) to less than 50 percent in turbid water (average turbidity of 4500 ppm). He suggested that oxidation of the organic fraction produced the low oxygen levels. Platner (1946) suggested the same process regarding the Mississippi River.

Temperature

110. Turbidity and suspended materials have been implicated in altering the temperature regime of an aquatic environment (Bartsch, 1959; Ellis, 1936; Goldman and Wetzel, 1963; Welch, 1952), although data and studies are few. Most studies have been based on the premise that turbid waters deep enough to stratify would be subject to fewer fluctuations in temperature than clear water (Wallen, 1951). Much of what is known concerning the relationship between turbidity and suspended materials and temperature is based upon the results of Ellis (1936).

111. Cairns (1968), reviewing suspended solids standards for the protection of aquatic organisms, states that the reduction in temperature fluctuations is probably of little importance. This is due to the fact that other major adverse affects, whether physical, chemical, or biological, would occur before a concentration level of suspended

material sufficient enough to produce significant temperature changes could be reached.

Recreation and aesthetics

112. In addition to the potential harmful effects suspended materials may have, there are a number of potential problems related to recreation and aesthetics. The coastal zones provide recreation and beauty for the 60 percent of the Nation's people dwelling there. Oceans provide swimming, boating, water skiing, and sport fishing, as well as wildlife viewing opportunities.

113. Because sediment-laden water reduces water clarity, inhibits the growth of plants, displaces water volume as sediments settle, and contributes to the fouling of the bottom, the prevention of unnatural quantities of suspended sediments or deposit of sediments is desirable.

114. David (1971) found that, although water pollution is perceived by the general public to be of increasing concern and that the public has rather definite ideas about what constitutes a description of pollution, too often aesthetic criteria are used. She discovered that the most widely used indicators of water pollution seem insufficient in light of the public definition of and concern about water pollution. Most of the respondents in her survey, conducted among adults in Wisconsin, mentioned algae and murky, dark water, but did not often mention attributes such as chemicals or disease-producing bacteria that are not readily detected by the human sensory system.

Primary Production

115. Phytoplankton and aquatic plants are the primary producers in aquatic environments. Using inorganic substrates (nutrients, water, and carbon dioxide), they synthesize organic matter with the release of oxygen during a reaction known as photosynthesis. The source of energy for this reaction is solar light energy. The quality, intensity, and duration of light influence photosynthetic rates in aquatic plants. That depth at which oxygen production from photosynthesis equals oxygen consumption through respiration defines the compensation point. The

compensation point is approximately equal to that depth at which light penetration is 1 percent of the surface intensity. Clearly, then, effective light penetration varies with the transparency of the water, as well as a number of other factors, and the compensation depth may vary from less than 1 m to over 100 m in the open ocean (Raymont, 1963).

116. There are a number of factors affecting primary production. Brylinsky and Mann (1973) analyzed the factors governing productivity in 43 lakes and 12 reservoirs, distributed from the tropics to the arctic. They found that in the whole body of data, variables related to solar energy have a greater influence on production than variables related to nutrient concentration. Turbidity can restrict the euphotic (photosynthetic) zone while suspended materials can contain large quantities of nutrients.

117. Odum and Wilson (1962) found that additions of turbidity-producing material into the water column can indirectly stimulate photosynthesis. If respiration exceeds photosynthesis, the accumulation of inorganic nutrients associated with the sediment could, in time, stimulate photosynthesis. Thus the turbid mixtures of organic and inorganic material both interfere with photosynthesis by shielding light and stimulate it by indirectly raising inorganic nutrient levels (Odum and Wilson, 1962). Turbidity and suspended materials, produced as a result of natural and/or man's activities, can both promote and inhibit primary production, and therefore can be of substantial importance. Dredging and the disposal of dredged material are of increasing importance and magnitude. Unfortunately, because so little information is available on the relationship between these activities and primary productivity, it is difficult to relate the time-duration of turbidity caused by dredging to the time required for algal stimulation, dilution around disposal sites, etc.

Freshwater environments

118. The production of phytoplankton represents the base of the food chain in most natural lakes and man-made impoundments. Because of the importance of phytoplankton to the food chain, limnologists and aquatic biologists have devoted considerable attention to the effects

of turbidity and suspended materials on the development of phytoplankton populations. Much of this work has been conducted in Lake Erie, and has been summarized by Beeton and Chandler (1963), Davis (1966, 1969), and Schelske and Roth (1973).

119. Chandler (1942) and Chandler and Weeks (1945) were two of the first to discuss the relationships between light penetration, turbidity, and phytoplankton production in western Lake Erie. During their studies, they measured a number of physicochemical parameters and phytoplankton crop from 1941 through 1942. They concluded, after comparing their physicochemical data with phytoplankton pulses, that the vernal pulses of phytoplankton were due primarily to variations in turbidity, which affect the photosynthetic activities of phytoplankters. Therefore, the small size of the 1942 phytoplankton crop, which was only 19 percent of the 1941 spring crop, was attributed to physical rather than chemical factors, specifically high turbidities. Chandler (1942) summarized by stating that biological implications of turbidity and its variations in western Lake Erie include composition, size, duration, and time of occurrence of phytoplankton pulses; rate of photosynthesis at various depths; and position of the compensation point of higher aquatic plants and phytoplankters.

120. Verduin (1951, 1952, 1954, 1956) examined primary production in western Lake Erie from 1949 to 1955. While most of the data in Chandler (1942) and Chandler and Weeks (1945) are based on samples from a single locality, Verduin (1954) obtained data from several extensive areas to determine the relationships between turbidity and phytoplankton. Verduin (1951) noted that the westward extent of the diatom communities each year was limited by the presence of turbid areas which frequently formed visible lines. The diatom populations in the turbid water west of the lines attained a density less than one-sixth that of the clear water populations. However, phytoplankton crops showed only slow rates of increase even in the clearest waters. As the season progressed, the phytoplankton crops increased most rapidly in the waters of intermediate turbidity.

121. After analyzing turbidity ranges, nutrient sources,

phytoplankton standing crops, and especially the physiography of the western basin, Verduin (1954) concluded that the large differences in growth for phytoplankton were due to both physical and chemical parameters. He speculated that the maximal phytoplankton crops may arise only when an influx of clear water mixes with turbid, fertile water, creating large water masses that have enhanced fertility plus sufficient transparency to promote utilization of the fertilizer by the phytoplankton.

122. Griffith (1955) examined phytoplankton yield in Lake Michigan. She was in general agreement with Chandler (1942) that a period of high turbidity preceded a high plankton pulse and that during the pulse the turbidity was relatively low.

123. Meyer and Heritage (1941), also working in Lake Erie, found that although most of the turbidity was due to silt or finely divided organic detritus stirred up from the bottom in some seasons blooms of various species may become sufficiently dense to contribute to the turbidity of the water. Crum and Bachmann (1973) observed the same results in several Iowa lakes where the turbidity from plankton blooms prevented the growth of macrophytes by reducing water transparency.

124. Plumb (1973) investigated the possibility of Lake Superior algae populations using taconite tailings as a nutrient source. Although Andrew and Glass (1970), Goldman (1970), and Shapiro (1970) reported a stimulatory effect of taconite tailings on algae growth, Plumb (1973), utilizing extensive laboratory studies, could not support their position.

125. Numerous other studies have dealt with primary productivity in lakes and reservoirs. Harris and Silvey (1940) found that plant growth in several Texas reservoirs may be benefited by silt from rich alluvial soils. Goldman and Wetzel (1963) reported that the primary productivity of Clear Lake, California, was almost entirely limited to the phytoplankton and bacteria. Because of the high turbidity, the littoral development of higher aquatic vegetation was restricted to emergent types along the periphery of the lake in spite of the extensive shallow areas.

126. Jackson and Starrett (1959) investigated the correlation between turbidity (caused by resuspended particles), wind velocity, and presence or absence of vegetation in Lake Chautaugua, Illinois. Turbidity of the lake ranged from 25 to 800 ppm and sago pondweed, *Potamogeton pectinatus*, was the most abundant submergent plant. They found that wind velocity had little or no effect upon turbidity when vegetation was present in the lake or in areas where water depth exceeded 5.8 ft. When depths were less than 4.8 ft and vegetation was absent, turbidity tended to vary with wind velocity.

127. Although red tides (usually defined as zones of high phytoplankton concentration adjacent to land and typically composed of dinoflagellates) have been reported for many marine coasts, there have been few reports of similar phenomena in freshwaters. Horne et al. (1971) reported a freshwater red tide on Clear Lake, California. They postulated that the red tide was due to winter floods followed by a calm period with clear skies that provided dissolved organic material and high insolation. The high inorganic turbidity present at that time prevented rapid growth of the dominant spring-summer alga, *Aphanizomenon flos-aguae*, but did not preclude the bloom of *Peridinium pernardii* because of its phototactic mobility. Horne et al. (1971) noted no toxic effects on the flora and fauna of the lake.

128. While numerous studies have considered the relations between production and turbidity and suspended material in lakes, few studies have dealt with the subject in rivers and streams. Berner (1951) found that in the lower Missouri River turbidity was commonly greater than 3000 ppm and, as a result, there was a paucity of phytoplankters. Since its impoundment through the construction of five dams, the less turbid water in the reservoirs of the Missouri River supports an increased algae growth, sometimes to the point of causing problems in municipal water supplies (Bartsch, 1959). However, even though turbidity may be reduced by more than 50 percent in the larger reservoirs, Benson and Cowell (1968) considered turbidity to be the strongest limiting factor to plankton abundance.

129. Phytoplankton density and diversity in several of the major

rivers of the United States was the subject of a study by Williams (1964). He attributed plankton pulses in the upper Columbia River to the influx of suspended nutrients. In the Missouri River and the upper portions of the Red River and Rio Grande, the highest plankton populations occurred when the soil of the area was frozen and less suspended material was carried into the river. With the runoff from snow and rain, higher turbidities returned and plankton density decreased.

130. The limnology of the middle Mississippi River was examined by Dorris et al. (1963). They reported that river discharge exerted the overriding influence on most factors, including photosynthetic productivity. Peaks of photosynthetic production coincided with low levels of stream discharge and low silt levels. Galtsoff (1924) also examined the plankton in the Mississippi River, but worked in the upper section where the river forms two lakes, Lake Pepin and Lake Keokuk. Total plankton production was greater in the lakes than in adjacent parts of the river. He attributed the differences to current velocity and corresponding amounts of detritus, silt, and sand in suspension.

Estuarine environments

131. Because phytoplankton are ubiquitous, it is usually the case that most marine and freshwater ecosystems are based upon the primary production of phytoplankton. However, in many estuaries emergent and submerged aquatic plants are often the predominant primary producers. The major sources of estuarine primary production include macrophytes (marsh and sea grasses, mangroves, terrestrial plants) and benthic microalgae (benthic and epiphytic diatoms, dinoflagellates, filamentous green and blue-green algae), as well as phytoplankton (Odum et al., 1973). Increasing evidence (Day et al., 1972; Pomeroy, 1960; Schelske and Odum, 1961) suggests that the macrophytes are the most important primary producers, while the phytoplankton appear to be the least important, at least in estuaries less than 10 m deep (Teal, 1962). Thus, the production from these major sources provides most of the material that constitutes the detritus-based structure of estuarine foodwebs.

132. The release of silt, clay, and fine sand-sized particles (organic and inorganic) into the water column is a dominant feature of

bay and estuarine areas (Sherk, 1971). These releases may be caused by beach erosion, river contribution, storm agitation, dredging, and dispersal of dredged material. An important effect of the resulting suspended load is reduced light penetration, which limits the depth of water in which light intensity is sufficient for the rate of photosynthesis (i.e., oxygen production) to exceed the rate of respiration (i.e., oxygen consumption) (Sherk et al., 1976).

133. Williams (1973) studied nutrient levels and phytoplankton productivity and found that in shallow estuaries rates of production tend to follow the seasonal cycle in water temperature. His nutrient enrichment studies indicated that the available nitrogen commonly limited production, while there was usually ample phosphorus.

134. In shallow estuaries, highest annual production per unit area is usually near the mouth of the estuary even though highest production per unit volume is normally in the shallower and more turbid water near the head (Herman et al., 1968; Stross and Stottlemyer, 1965; Thayer, 1971). Williams (1973) explained this by saying that "the greater clarity and depth of water near the mouth of such estuaries more than compensates for greater standing crop of algae and rate of production per unit volume found near the surface of the turbid water."

135. Stross and Stottlemyer (1965) measured standing crop and photosynthesis rates at 22 stations along a 29-mile segment of the Patuxent River Estuary. In the shallow upstream stations, adequate nutrient supplies were available, suggesting that this was potentially the most productive area on a volume basis. The downstream end was only one third as productive on a per-unit-volume basis. However, upstream light attenuation by the inorganic suspended load limited the euphotic zone to the upper 1 m, and the daily measured rate of production on an areal basis was 1.2 gC/m^2. In the downstream stations, which had a euphotic zone down to 5 m, the daily rate of production was 1.8 gC/m^2. On an areal basis, the upstream stations were less productive than those downstream. Stross and Stottlemyer (1965) suggested that upstream it was possible that nutrient uptake exceeded photosynthetic demand and that the cells were more shade tolerant than those

further downstream. Both could contribute to rapid rates of photosynthesis in samples incubated at subsaturation light intensities.

136. An extensive study of several Texas bays was conducted by Odum and Wilson (1962). In many of the Texas bays, the release of large quantities of organic-laden silts and clays into the water column from beach erosion, river contributions, storm agitation, or dredging is a dominant factor. Odum and Wilson (1962) reported that turbidity affected total metabolism by reducing light penetration which reduced primary production. Concurrently, respiration was stimulated by the introduced organic matter. In the same study, they noted that when the bottom was within the euphotic zone, high production was possible even in highly turbid water. If mixing carried the phytoplankton below the euphotic zone (or "critical depth" of Ragotzkie, 1959) and shading occurred for a sufficiently long period of time for cell attrition to exceed photosynthesis, the phytoplankton population could not survive.

137. Odum and Wilson (1962) also suggested that the introduction of large quantities of organic matter in the turbid waters of San Antonio and Baffin Bays, during flooding in Matagorda Bay, in a Louisiana bay that received marsh detritus, and in back bays receiving rivers, was responsible for respiration having exceeded photosynthesis in those areas.

138. Odum (1963) measured chlorophyll values and productivity in turtle grass beds during a dredging and disposal operation in Redfish Bay, Texas. Decreased productivity and an imbalance of respiration over photosynthesis were noted following dredging during the spring. However, Odum (1963) reported exceptional growths the following year and suggested that dredging may stimulate productivity by adding nutrients, as first suggested by Ingle (1952) and Ingle et al. (1955).

139. Taylor and Saloman (1968), working in Boca Ciega Bay, Florida, noted that turbidity limited bottom primary production, but could detect no consistent differences between dredged and undredged sites.

140. A comparison of phytoplankton production between natural and altered areas in West Bay, Texas, was conducted by Corliss and Trent (1971). Average gross production, measured in mgC/ℓ/day, in the dredged

canals was 8 percent higher than in the natural marsh and 48 percent higher than in the open bay during June, July, and August. The average net production in the canals was 13 percent higher than in the marsh and 51 percent higher than in the bay. Statistically the averages of gross and net production in the canal and marsh were significantly greater than in the bay, while differences between the canal and marsh were not significant. The differences in production between stations were related to turbidity.

141. In a long term study, Vittor (1972, 1973) was concerned with identifying and describing the impact of a dredging project on the estuarine environment of D'Olive Bay, Alabama, with respect to the water quality effects of disposal effluents. The investigation consisted of four phases: prior to dredging; during dredging operations; after dredging; and 8 months after completion of dredging. All parts of D'Olive Bay experienced turbidity fluctuations due to winds and rainfall runoff from a highway construction site. Vittor (1972) reported no general increase in turbidity due to dredging during phase two. Mean values at the dredging site prior to and during operation were 43 and 41 JTU's, respectively. However, the resuspension of mud flow sediments at station 9 below the dredging site during phase three produced periodic values as high as 120 JTU's. Although there was also no consistent relationship between turbidity from dredging operations and productivity at most sites, the resuspended sediment at station 9 decreased the total organic production, as measured during phase one, by 50 percent. Wind-induced turbidity had a greater impact than that typically caused by dredge effluents (Vittor, 1972).

142. The effects of turbidity and suspended material on primary production in Chesapeake Bay has been investigated by numerous individuals. Flemer (1970) and Flemer et al. (1968) studied the effects of the overboard disposal of 1.1×10^6 m^3 of sediments from the upper Chesapeake Bay approach to the Chesapeake and Delaware Canal. Background turbidity levels were found to be high because of the redistribution of bottom sediments by the wind, tidal currents, and flows from the Susquehanna River (Biggs, 1968). Biggs (1970) calculated that of the

total seston entering the upper bay from the Susquehanna River, 1.6×10^5 tons (26 percent) consisted of organic matter fragments. The natural turbidity limited production severely in upper Chesapeake Bay. During the period of disposal, the water transparency was reduced below background levels and production was reduced to about one third of that outside of the dredged material zone. However, Flemer (1970) and Flemer et al. (1968) reported that the reduced transparency was of short duration, that dredged material disposal released beneficial nutrients, and that no gross effects from the disposal of fine materials were observed.

143. Primary production of the plankton community in the estuarine waters near Sapelo Island, Georgia, was calculated by Ragotzkie (1959). The estuarine waters around the area were highly turbid making light penetration the principal limiting factor. Mean net annual planktonic community production, including organic detritus and its associated bacterial flora, averaged -0.038 gmC/m^2/day. Because the metabolic activities of all other animals in the estuary would tend to increase the net loss of organic matter from the system, Ragotzkie (1959) suggested that an outside source of organic matter was necessary to account for the negative production. The most likely source was an adjacent salt marsh where Smalley (1959) estimated the net production to be 1 gmC/m^2/day.

144. The Tampa Bay Estuary, Florida, and vicinity has been one of the most completely studied areas in the Gulf of Mexico. Taylor (1973) summarized literature on the area that has appeared since the early 1950's. He cited the major sources of turbidity as being the resuspension of fine bottom sediments by high winds and the introduction of suspended material from land drainage and sewage, as well as plankton populations. The highest turbidity values were recorded intermittently near dredging operations, while the average annual turbidity range was only between 4 and 10 JTU's.

145. As discussed previously, there are a number of factors responsible for red tides and plankton blooms, most of which occur in estuarine and coastal waters. Phytoplankton blooms in estuaries often occur where nutrient distribution, maximum exposure to optimum light, and adequate

residence time for cell division are most favorable. Welch et al. (1972) examined the relationship between periphytic and planktonic algal growth, and hydrographic factors in the Duwamish estuary (Seattle, Washington). The estuary was highly enriched, with phosphorus and nitrogen concentrations exceeding the levels expected to limit algal growth (Welch, 1969). Periphyton growth was related to incident light intensity and decreased with increased turbidity. Welch (1969) suggested that the lack of a concurrent phytoplankton bloom supported his conclusion that favorable hydrographic conditions (freshwater discharge, tidal range, thermal stratification) promote phytoplankton production, rather than nutrients. During the observed phytoplankton bloom, the introduction of treated sewage from an activated sludge plant did not appear to contribute to the distribution of the bloom in the already highly enriched estuary (Welch, 1969).

146. Conomos and Peterson (1973) described the relationship between turbidity maxima and phytoplankton in San Francisco Bay, California. The abundance and composition of the suspended particulate matter in the turbidity maximum changed seasonally. With the decline of high winter river inflow from the Sacramento and San Joaquin Rivers, the concentration of riverborne suspended particles decreased. During this period, the phytoplankton concentration in the turbidity maximum often increased fivefold, and the suspended particle concentration diminished by about 50 percent (Conomos and Peterson, 1973). By late summer, the phytoplankton and zooplankton constituted a substantial fraction of the turbidity maximum, having increased from a winter concentration of 3 percent to a summer concentration of 30 percent. Conomos and Peterson (1973) termed this substitution of biogenous matter for lithogenous matter a "plankton maximum." They believed that phytoplankton production was greater at the turbidity maximum than elsewhere in the estuary because of the following: riverborne suspended particulate matter was at its minimum concentration and insolation was maximal; there was availability of sufficient nutrient concentrations; and the nature of the turbidity maximum was such that it was the zone of longest residence time, permitting growth of a greater plankton population.

147. Few studies exist on the contribution of bacteria to turbidity. Oppenheimer and Jannasch (1962) compared the bacterial populations in turbid and clear sea water near Port Aransas, Texas. The extensive, shallow, marine bay system of the Central Texas coast is noted for turbidity caused by the presence of clays, detritus, and living organisms, and visibility is often limited to a few centimeters. Bacteria were found to represent a substantial amount of the total particulate load. Of a total suspended particulate load of 39.9 g/m^3 dry weight, the amount of dry bacterial mass was 1.16 g/m^3, or about 3 percent of the total load (Oppenheimer and Jannasch, 1962). The calculated bacterial biomass was similar to the values obtained by ZoBell and Feltham (1942) for a marine mud flat in Mission Bay, California.

148. Although there are very few studies available, several investigators (Gunnerson and Emery, 1962; Olson et al., 1941; Welch, 1952) have suggested that suspended sediment may trap phytoplankton, carrying the phytoplankton to the bottom as the sediment settles. Gunnerson and Emery (1962), working in San Pedro Basin, California, provided evidence suggesting that the sinking of plankton along with the suspended sediment was the result of a turbidity current originating on the continental shelf.

149. Usually if turbidity increases, photosynthetic activity decreases. North and Schaefer (1964) described an unusual effect of turbidity, produced by waste discharges, on kelp beds off the California coast. With an increase in turbidity, North and Schaefer (1964) noted a shoreward movement of plants along the gently sloped bottom. The result was the same net photosynthesis, but at a slightly decreased depth.

Selected Phyla of Invertebrates

150. Many invertebrate species are of considerable importance to man from an economic and commercial standpoint. Invertebrates also occupy important positions in the food web. Many filter-feeding species are capable of removing large quantities of suspended material from the

water column, thereby reducing turbidity and promoting sedimentation.

151. The following section is a discussion of the effects of turbidity and suspended material on selected groups of invertebrates in a sequence proceeding from the simpler to the more complex phyla.

Phylum Coelenterata

152. Coelenterates, such as the corals, occur in marine waters. Coral reefs are built by small polyps capable of constructing massive skeletal structures of calcium carbonate. Reefs are characterized by high population density and complex nutrient chains. Reef-building corals are mainly restricted to the shallow waters of tropical seas between latitudes 28°N and 28°S. They flourish best in water temperatures above 20°C and from the surface to depths of about 120 ft.

153. Levin (1970) and Roy and Smith (1971) summarize the effects of turbidity and suspended sediments, derived from dredging, on coral reefs. Large concentrations of suspended material and increased turbidity are usually detrimental to coral reefs. Turbidity reduces the light available to the symbiotic coralline algae for photosynthesis and suspended material interferes with the feeding activities of the coral polyps.

154. Marshall and Orr (1931), Mayer (1924a,b), and Vaughan (1916) showed that many corals are capable of removing suspended material from their surfaces by ciliary action, although the capacity to accomplish this was variable. Those species of corals inhabiting the seaward edges of a reef were not as capable of removing sediment nor as tolerant of turbidity as were the nearshore forms.

155. Mayer (1924a,b) found that the corals that were most resistant to suspended material were various species of the Samoan coral genus, *Porites*. His conclusion was based on field observations of coral growth and an in situ study of corals suspended in cages in areas of high turbidity in Pago Pago Harbor, American Samoa. Levin (1970), however, citing the studies of Edmondson (1928) and Marshall and Orr (1931), concluded that the Hawaiian species of *Porites* would be most susceptible to turbidity from dredging operations.

156. The existence of reefs off the Rewa River in Fiji has been

cited by Ladd and Hoffmeister (1936) as evidence that reefs can survive under extremely turbid conditions caused by land runoff. Shepard (1963) reported that reefs off the south coast of Molokai, Hawaii, were found in areas of turbid water rather than clearer water. He suggested that the lower salinities near the mouths of rivers were more important in determining reef formation.

157. Roy and Smith (1971) noted that coral reefs growing in the shallow lagoon of Fanning Island (Central Pacific Ocean) developed in both turbid and clear areas where water visibilities ranged from 2 to 15 m, respectively. The measured calcium carbonate suspended load was 3.5 mg/ℓ in the turbid area and 1.0 mg/ℓ in the clear water. Because of the shallow nature of the lagoon, the light intensity at the bottom was never less than 5 percent of the incident surface light and was never considered to be limiting. The reefs in the turbid area were ecologically and structurally different from the ones in clear water, but they were still living reefs.

158. Brock et al. (1965, 1966) reported that turbidity from dredging operations adversely affected over 7000 acres of reef and lagoon on Johnston Island. Coral mortality in the turbid water areas ranged up to 40 percent.

159. Griffin (1974), discussing the effects of a dredge-and-fill project in the Florida Keys, reported that the coral patch reef did not undergo any detectable change during the year of nearby dredging. The dredge project yielded 2×10^9 mg suspended sediment/working day. This was 5 percent of the total natural load of the entire 21-mile inshore park area (Griffin and Antonius, 1974). Following termination of dredging, a quantitative line transect of the reef disclosed that 72 percent of the coral was alive and 28 percent dead. The percentage of dead corals was not considered to be unusual for a highly stressed inshore reef under natural conditions.

Phylum Mollusca

160. This phylum includes such organisms as slugs and snails (class Gastropoda), squids and octopuses (class Cephalopoda), and clams, oysters, and mussels (class Bivalvia). The bivalves are predominately

filter feeders and play an important role in reducing turbidity by removing suspended material from the water column. There are also a number of species of bivalves that are of commercial importance, including the American oyster (*Crassostrea virginica*), the quahog (*Mercenaria mercenaria*), and the common edible mussel (*Mytilus edulis*). Consequently, many of the field and laboratory studies have dealt with this class and the above species.

161. One of the least studied factors of molluscan environments is turbidity. A review of the literature on the ability of bivalve adults, larvae, and eggs to tolerate turbidity and suspended material may be found in the paper by Loosanoff and Davis (1963).

162. Adult freshwater bivalves. Very few studies are available concerning the effects of turbidity and suspended material on freshwater bivalves. Ellis (1936) recognized the effects of silt on freshwater mussels. Silt limited light penetration, thereby influencing the mussel's phototactic responses and reducing the reproduction of the phytoplankton on which the mussels fed. Laboratory tests indicated that feeding was inhibited by suspended silt. Those mussels in turbid water were closed 75-90 percent of the time, while those mussels in clear water were closed only about 50 percent of the time (Ellis, 1936).

163. Adult estuarine bivalves. Much of the work on estuarine and marine bivalves has dealt with the adults, although several of the more recent studies have considered the effects of suspended material on larvae and eggs. Because bivalves are more or less stationary, one of the most detrimental consequences of high concentrations of suspended material is sedimentation. Sedimentation is not the subject of this report; however, many of the following studies discuss this aspect as well, because although the effect of turbidity and suspended material may not be lethal, quite often sedimentation is.

164. Lunz (1938), studying the American oyster in Duval County, Florida, noted no serious effects due to suspended material from an adjacent dredging operation. Those oysters exposed to disposal area runoff also survived, and the dredging operations had no adverse effects on either spawning or settlement of larvae (Lunz, 1938).

165. Under laboratory conditions, Wilson (1950) subjected oysters to suspended sediment concentrations of from 4 to 32 g/ℓ. He found that extended exposure to these high concentrations could be detrimental. However, after studying the effects of shell dredging in Copano Bay, Texas, Wilson (1950) found no correlation between number of larvae set and distance from the dredge.

166. Ingle (1952) suspended oysters in baskets adjacent to an operating dredge in Mobile Bay, Alabama. The number of mortalities recorded were not considered to be excessive and the oysters, when opened, were in "excellent appearance." Ingle (1952) suggested that a possible beneficial effect of dredging was that it stirred up organic detritus and he stated that "oysters fattened quickly in finely particulate and suspended material."

167. Effects of dredging on oysters were studied in shallow bays in Louisiana by Mackin (1956, 1962). Studies in the field from 1947 to 1950 showed that there was an inverse relationship between turbidity and mortality of oysters (Mackin, 1956). Oysters in the lower part of Barataria Bay, where salinities were high and turbidity was low, had consistently heavy mortality. In the fresher waters above Barataria Bay, turbidity was higher and the mortality rate was only one third to one half that in the lower bay.

168. In laboratory aquaria, Mackin (1956) subjected oysters to turbidities of mud from 100 to 700 ppm. Oysters fed in suspensions up to 700 ppm without any apparent problems, and mortality was no higher than in the controls.

169. Field and laboratory studies were conducted by Mackin and Hopkins (1962) to examine oyster mortality in relation to oil fields in Louisiana. Field experiments did not show any adverse effect upon the setting, survival, growth, or fattening of oysters. Laboratory experiments showed that crude oil, water extracts, and barium sulfate, the chief constituent of drilling mud, had no effect on survival of oysters over periods of several months. It was concluded (Mackin and Hopkins, 1962) that oil production factors like those tested were not responsible

for the recorded oyster mortalities in the area, but rather high temperature and high salinity.

170. McKinney and Case (1973) monitored the effects of turbidity and siltation on oyster reef communities in San Antonio Bay, Texas. They found that growth of oysters suspended in experimental baskets was not affected by suspended silt from a nearby shell dredge. However, oyster populations located on the bottom and suspended from the dredge itself were killed by the accumulation of fine particles from the discharged wash water.

171. A number of studies (Anderson et al., 1973; Butler and Engle, 1950; Gunter, 1953) exist on the effects of high turbidities associated with floodwaters on oyster-producing areas. Anderson et al. (1973) reported several adverse effects related directly or indirectly to the passage of Hurricane Agnes in Chesapeake Bay. Oyster mortality was high (up to 100 percent in some areas) and Anderson et al. (1973) correlated this with low salinities rather than high suspended sediment loads or low dissolved oxygen levels. High mortalities were also noted among the soft-shell clams, *Mya arenaria*. Although the clams were already suffering from thermal stress, high turbidity and low salinity were considered as possible additional contributing factors.

172. Butler and Engle (1950) and Gunter (1953) examined the effects on oysters of the 1950 opening of the Bonnet Carré Spillway, designed to protect New Orleans by diverting Mississippi River floodwaters into the Gulf via Lake Pontchartrain. The data indicated a progressive decrease in salinity and increases in turbidity and suspended material. The average suspended silt load at the spillway was 1068 ppm sediment, while at the lakeside the sediment load dropped to 398 ppm sediment. Thus most of the material was deposited in the floodway and never reached the oyster reefs. Gunter (1953) stated that in spite of 20-25 percent mortality, oysters were benefited rather than harmed by the floodwaters because certain injurious organisms were destroyed and large quantities of nutrient salts were brought into the area.

173. As filter feeders, bivalves are particularly susceptible to mechanical or abrasive action (i.e., clogging of gills, irritation of

tissues, etc.) of suspended sediments (Cairns, 1968). Several studies have considered this relationship. Loosanoff and Tommers (1948) found that the oyster fed most efficiently when the number of food microorganisms in the water was relatively small. They studied the rate at which the oysters pumped water through the gills using suspended concentrations of silt of from 0.1 to 4.0 gm/ℓ. Reduction in pumping rates ranged from 57 percent (0.1 gm/ℓ) to 94 percent (4 gm/ℓ). Similar results were obtained when kaolin, chalk, and fuller's earth were used. When the flow of turbid water was replaced by regular seawater, pumping rates returned to normal.

174. Loosanoff (1961) found that small quantities of silt sometimes stimulated normal activities of adult and larval oysters. Loosanoff (1961) attributed this to the absorption of toxic substances by particles of suspended materials present in the water and to slight mechanical stimulation of the gills of adults. His data indicated that lamellibranchs in general fed most effectively in relatively clear water.

175. Using *M. edulis*, as well as several other bivalve species, Chiba and Ohshima (1957) found that concentrations of 1 gm/ℓ of suspended bentonite clay did not reduce the pumping rate in any of the species tested. With increasing concentrations, the pumping of *M. edulis* increased.

176. Loosanoff (1949) demonstrated that oysters, when given various suspensions of microorganisms, selected their food not only quantitatively but also qualitatively. The oysters rejected certain plankton forms, through the formation of pseudofeces, while selecting others that differed physically and/or chemically.

177. Lund (1957c) discovered that the quantity of inert matter (fuller's earth, etc.) and food (plankton) in a suspension in sea water determined in part the volume of food intake and the volume of material rejected. In seawater of low turbidity, an increase in the volume of water filtered compensated for low concentrations of suspended material.

178. Several other authors (Jorgensen, 1955, 1960; Jorgensen and Goldberg, 1953) also noted that the particle size of the suspended material determines whether a substance is retained by a filter feeder.

Jorgensen and Golberg (1953) reported that the oyster was able to filter and clear a graphite suspension with a particle size of 2-3 μm 5 to 10 times faster than a suspension with a particle size of < 2 μm.

179. Pratt and Campbell (1956) discussed the results of a 3-yr study on environmental factors affecting growth in the quahog, *M. mercenaria*. Growth rates proved to be a function of the abundance of small plankton diatoms. When different sediments were used, growth rates were retarded in sediments with a high silt-clay content. Pratt and Campbell (1956) suggested that the inhibition of growth in fine sediments may have resulted in part from the interruption of feeding and the additional expenditure of energy needed for the frequent clearing of the animals' filtering apparatus. Peddicord (1976, 1977) worked with the brackish water clam *Rangia cuneata* in mud and sand bottoms and made a similar suggestion in partial explanation of lower growth rates in muddy bottoms.

180. The responses of the scallop, *Placopecten magellanicus*, and the mahogany quahog, *Arctica islandica*, to suspensions of kaolin were studied by Stone et al. (1974). Both species produced increased amounts of mucus when cleaning the gills of kaolin. The production of increased amounts of mucus required the use of stored energy reserves that would normally be used for other functions (e.g. gametogenesis). The implication was that exposure to high concentrations of suspended solids might impair reproduction (Stone et al., 1974).

181. Peddicord et al. (1975) presented extensive laboratory data on the tolerance of a variety of species to suspended solids in relation to temperature and dissolved oxygen. Preliminary experiments on the lethal effects of suspended kaolin indicated a wide range of sensitivities among the species studied. The bivalve species *Tapes japonica* and *M. edulis* were exposed to suspended kaolin concentrations of 100 gm/ℓ. The percent mortality for *T. japonica* after 10 days exposure was 0 percent, while for *M. edulis* it averaged 10 percent for both 2.5-cm and 10-cm individuals after 5 and 11 days, respectively. *Mytilus californianus* was more sensitive than either of the above species. For 10-cm mussels the estimated lethal concentration for 50 percent of the

animals (LC_{50}) after 200 hrs exposure was 96 g/ℓ suspended kaolin.

182. In a subsequent, more intensive study, *M. edulis* were subjected to several temperature and dissolved oxygen regimes while in various concentrations of suspended bentonite. Peddicord et al. (1975) observed a greater mortality at high temperature than at low. They suggested that although mussels remained closed for the first few days of the test, the higher metabolic rate at the higher temperatures hastened their opening and increased their exposure to bentonite particles. In oxygen consumption experiments, the data indicated a decrease in oxygen uptake with increasing suspended bentonite concentration.

183. The experimental conditions also resulted in loss of byssal attachments by *M. edulis* after much shorter exposure times to suspensions of bentonite than those causing deaths. Reish and Ayers (1968) observed the same results when *M. edulis* were exposed to low dissolved oxygen levels. Peddicord et al. (1975) suggested that the loss of byssal attachments may be an early and sensitive indicator of effective death.

184. Estuarine bivalve larvae and eggs. The effects of turbidity-producing materials on the development and growth of estuarine bivalve eggs and larvae were examined by Davis (1960) and Davis and Hidu (1969). Davis (1960) found that some quahog (*M. mercernaria*) eggs developed normally in concentrations up to 4 g/ℓ of clay, chalk, or fuller's earth, although the percentage developing normally decreased as the concentration of the suspended materials increased. No clam eggs developed normally in silt concentrations of 3.0 or 4.0 g/ℓ. Larvae were unable to grow in concentrations of kaolin, clay, chalk, or fuller's earth as high as those at which some eggs developed, while at silt concentrations of 4.0 g/ℓ there was no appreciable mortality of clam larvae.

185. Davis and Hidu (1969) found that as little as 0.188 g/ℓ of silt caused a 22 percent decrease in the number of oyster eggs developing normally, where fuller's earth and kaolin had no significant effect until concentrations exceeded 1 g/ℓ and 2 g/ℓ, respectively. Survival of European oyster larvae *Ostrea edulis* was less affected by silt, kaolin, and fuller's earth than were the larvae of either American oysters or quahogs. Davis and Hidu (1969) noted that bivalve larvae

grew faster in low concentrations of turbidity-producing substances than in clear seawater. They attributed this to the ability of suspended particles to chelate or adsorb toxins present in larval cultures and suggested that the optimum concentration of suspended material probably depends upon the amount of toxin to be chelated or adsorbed.

186. Gastropods. Few studies exist on the effects of turbidity and suspended material on gastropods. Harrison and Farina (1965) observed egg-laying and development of the eggs, in three species of freshwater planorbid snails, in relation to finely divided suspended solids. Concentrations in aquaria ranged from 190 to 360 ppm suspended solids. Results ranged from normal egg development in all concentrations (*Lymnaea natalensis*) to high mortality levels in both concentrations (*Bulinus globosus*). The third species (*Biomphalaria pfeifferia*) did not lay eggs in the water with 360 ppm suspended solids, but did so in the aquaria with 190 ppm suspended solids.

187. Johnson (1971) investigated the effect of turbidity on the rate of filtration and growth of the slipper limpet, *Crepidula fornicata*. The shell growth rate decreased as turbidity increased, perhaps because of inadequate food intake due to clogging of the filtering mechanism by suspended material. Filtration rates also decreased as the level of turbidity increased with a pronounced reduction as the concentration increased from 0.2 to 0.6 g/ℓ.

Phylum Arthropoda

188. The majority of the species of the phylum Arthropoda belong to the class Insecta. Although most insects are terrestrial, there are a substantial number of species that are aquatic as larvae and/or as adults. Most members of the class Crustacea, by contrast, are aquatic, and the class includes such commercially important species as lobsters, shrimp, and crabs. The zooplankton community typically includes many species of larval and adult crustaceans.

189. Class Insecta. Little is known concerning the effects of turbidity and suspended material on aquatic insects. Most studies have considered only the effects of silt and sand as related to the partial or complete smothering of the benthic fauna. Roback (1974) listed the

turbidity ranges for the waters in which several hundred species of insects (representing 10 orders) have been collected, but presented no discussion of this parameter.

190. Class Crustacea. Sherk et al. (1976) studied experimentally the effects of suspended sediments on the feeding activity of two typical Chesapeake Bay zooplankton copepods, *Eurytemora affinis* and *Acartia tonsa*. Adult zooplankters were fed suspensions composed of phytoplankton and sediments of various types and concentrations. Suspensions of fuller's earth, silica sand, or natural sediments caused reductions in the feeding rates in both copepods. Solids concentrations in excess of 250 mg/ℓ substantially reduced the ingestion rate for *E. affinis*, while *A. tonsa* reductions were noted at all concentrations above 50 mg/ℓ. Concentrations of phytoplankton greater than 250 mg/ℓ also caused reductions in ingestion. Sherk et al. (1976) concluded that nonselective feeding (i.e., taking up all particles indiscriminately) did not exist at high particle densities in these species. This would result in reduced consumption of food particles which, if continued over a long enough period, could cause a break in the food chain (Sherk et al., 1976).

191. The feeding of adult brine shrimp on mixed suspensions of food cells and soil particles was the subject of a study by Reeve (1963). He also found no selection between nutritive and nonnutritive particles and showed maximum filtration rate to be independent of the nature of the particles.

192. The effects of suspended material on the reproductive rate of *Daphnia magna* were studied by Robinson (1957). Suspended materials concentrations ranged from 0 to 1458 ppm total suspended material. Small amounts of suspended material were essential to optimal survival and reproduction. This effect appeared to be unrelated to the adsorptive capacities of the suspensions at low concentrations, but at higher levels some suspensions had a toxic effect which was apparently related to their adsorptive capacities. The total suspended material concentrations at which charcoal and montmorillonite, the most adsorptive materials studies, were toxic were about 100 ppm, while ground glass (tested at levels up to 98 ppm), India ink (676 ppm), kaolinite (392 ppm), and

pond sediment (1458 ppm) were not toxic at any of the tested levels.

193. McKinney and Case (1973) found that the barnacle, *Balanus eburneus*, was the predominant attached species on oyster reefs in San Antonio Bay, Texas. The fact that barnacles were settling out of the water column and attaching in great numbers during dredging operations indicated that suspended silt did not repel the planktonic larvae of these sessile crustaceans (McKinney and Case, 1973).

194. Paffenhofer (1972) studied the effects of "red mud," the fine-grained residue obtained during the extraction of aluminum from bauxite, on growth, body weight, and mortality of the marine planktonic copepod, *Calanus helgolandius*. The ability to molt through various larval stages to adults was substantially reduced in concentrations of 10 mg/ℓ of red mud. In addition, both growth and movement of adults were hindered and ovarian development in the female was absent.

195. Doan (1941, 1942) studied zooplankton population variations under conditions of changing turbidity in Lake Erie. He found that there were greater concentrations of zooplankters in the upper one meter of water during turbidity. The concentration of zooplankton near the surface was attributed to the mobility of the organisms and reflects their ability to adapt to small changes in turbidity. Chandler (1942), during his zooplankton investigations in the same region, also noted that microcrustaceans were more concentrated in the surface waters during periods of high turbidity. He suggested those organisms normally feeding upon microcrustaceans would also migrate vertically in response to the movement of the zooplankton.

196. Mortality of lobsters exposed to suspended sediment concentrations of 700 and 800 ppm turbidity from the Providence River, Rhode Island, was studied by Saila et al. (1968). Mortality was attributed to a toxic component and not the sediment concentration, because the lobsters showed no mortality when exposed to kaolin suspension up to 50 g/ℓ (47,200 ppm turbidity), 1,600 ppm of harbor sediments, or after 8 days exposure near a test dumping site for dredged material. Saila et al. (1968) also observed that water entering the branchial chamber was not completely free of particulate matter.

197. Barnard (1958) studied amphipod crustaceans in Los Angeles-Long Beach Harbors, California. A survey of the fouling and wood-boring animals showed that amphipods comprised one of the most abundant orders in turbid water. The high turbidity in the harbors was due to organic detritus from domestic and industrial pollution. In areas of adequate dissolved oxygen, the suspended solids in the seawater appeared to play a major role in determining the variability of the fouler population (Barnard, 1958). In relatively clear waters, boring organisms were abundant, while in turbid waters, fresh surfaces became quickly infested with polychaete worms and tube-dwelling amphipods. Barnard (1958) suggested a practical method of restricting borers from temporary uncreosoted wooden structures by providing an artificial turbidity, composed of food and silt, which would favor the formation of protecting mats of foulers on fresh surfaces.

198. Peddicord et al. (1975) investigated the relationships between suspended solids concentrations, temperature, and dissolved oxygen for several species of crustaceans. Their studies showed that the estimated 200-hour LC_{50} for kaolin of the spot-tailed sand shrimp, *Crangon nigromaculata*, was 50 g/ℓ. Similar sensitivities were also recorded for two closely related species, *C. franciscorum* and *C. nigricauda*.

199. The euryhaline shrimp, *Palaemon macrodactylus*, was less sensitive to suspended kaolin and the calculated 200-hour LC_{20} was 77 g/ℓ. The other decapod crustacean tested with kaolin was the commercial crab, *Cancer magister*. They were more sensitive than any of the shrimp species with a 200-hour LC_{50} of 32 g/ℓ. Extrapolation of data for the amphipod *Anisogammarus confervicolus* indicated a 200-hour LC_{20} of 35 g/ℓ, which was nearly identical to the 200-hour LC_{50} for *C. magister*.

200. Peddicord et al. (1975) found that at saturated dissolved oxygen and a suspended bentonite concentration of 36 g/ℓ, the percent survival of *C. nigricauda* at 10 and 18°C were very close at 95 percent and 75 percent, respectively. The influence of dissolved oxygen on tolerance of suspended bentonite by *C. nigricauda* was great, although the data were too erratic to quantify (Peddicord et al., 1975). Only a few deaths of the isopod *Lynidatea laticauda* occurred at 2-ppm

dissolved oxygen, and these were poorly correlated with suspended solids concentration.

201. Peddicord et al. (1975) also studied the influence of simultaneous variations in temperature and dissolved oxygen on the lethal effects of suspended bentonite on crustaceans. The data for *C. nigricauda* indicated that suspended solids concentration, temperature, and dissolved oxygen interacted in a highly complex, nonadditive manner to influence survival time. Survival was generally highest under conditions of low temperature and suspended solids and high dissolved oxygen. That temperature and dissolved oxygen greatly influenced suspended solids tolerance was illustrated by the fact that survival at 45 g/ℓ, 10°C, and 5 ppm did not differ significantly from that at 0 g/ℓ, 18°C, and 2 ppm dissolved oxygen (Peddicord et al., 1975).

202. The isopod suffered few mortalities in the multifactor experiment. Survival was lowest at 44 g/ℓ and 5-ppm dissolved oxygen at 18°C. None of the experimental variables had a statistically significant effect on length of survival and the few deaths that did occur were apparently random and not related to the experimental variables.

Fishes

203. Turbidity and suspended material may affect fishes directly or indirectly, and the following section primarily treats the former. Direct effects include lethal agents and those factors that influence physiological activities (reproduction, growth, development) or produce abrasive wear on tissues. Indirect effects include modifications to habitats and food chain organisms.

204. Because the literature concerning the effects of turbidity and suspended material on fishes is more extensive than for any other group of animals only the more significant and recent studies are discussed in detail in the following section. Much of the literature has been reviewed and summarized by Cairns (1968), Cordone and Kelley (1961), the EIFAC (1964), and Koski (1972). Many of these studies dealt with freshwater fishes, principally trout, and salmon. Extensive

bibliographies covering the more recent literature were presented in paragraph 71.

Lethal and sublethal effects

205. Although the literature on the effects of turbidity on fishes is extensive, few of the older studies related animal responses to the actual weight per volume concentration of particles in suspension. As noted by Peddicord et al. (1975), most studies correlated response with turbidity even though it is unlikely that the light absorbing and scattering properties of suspended particles directly affect animals.

206. Numerous authors (Barnickol and Starrett, 1951; Jackson, 1962; Krumholz et al., 1962; Larimore and Smith, 1963; Mills et al., 1966; Smith, 1968, 1971; Trautman, 1957), after completing sampling programs in several major river drainages and reviewing available faunal lists, concluded that the turbidity from suspended soil was the most important factor affecting the fish fauna. However, little qualitative and quantitative data were presented.

207. Ellis (1936, 1937) was one of the first investigators concerned with quantifying the physical and chemical characteristics of water to determine if it was suitable for freshwater stream fishes. Using available literature and his own bioassay work on the goldfish (*Carassius auratus*), Ellis (1937) summarized the lethal levels of 114 stream pollutants. He also grouped the pollutants, on the basis of their site of activity, into the following categories: those injurious to the gills and other external surfaces without absorption beyond the gills; those lethal substances absorbed by the gills; and those lethal substances absorbed from the gastrointestinal tract.

208. Wallen (1951) exposed a total of 380 fishes, representing 16 species, to varying concentrations of montomorillonite clay ranging up to a turbidity equivalent to that produced by 225,000 ppm standard silica flour. The response of the fishes to increased concentrations of clay followed a definite pattern and the symptoms were exhibited by all species, beginning when the concentration reached that equivalent to about 20,000 ppm of silica flour. The stages, as outlined by Wallen (1951), were as follows:

a. Momentary swimming at the surface and gulping air and water.

b. Leaning toward one side while remaining at the surface for several minutes.

c. Floating on one side for up to 30 minutes with an occasional swimming movement.

d. Floating with only occasional feeble opercular and pectoral fin movements until death.

209. Most individuals of all species tested endured exposure to suspended sediment concentrations producing turbidities equivalent to more than 100,000 ppm silica for over a week and finally died at turbidities equivalent to 175,000-225,000 ppm silica flour. Lethal turbidities resulted in death within 15 minutes to 2 hours following exposure and in those fishes that succumbed, the opercular cavities and gill filaments were clogged with clay particles. This coat of clay did not damage the tissues and if the fishes were transferred to clear water, they successfully expelled the accumulated solids. In sublethally turbid waters, swimming and aeration of the water allowed the fishes to avoid clogging of gills. Wallen (1951) concluded that the direct effect of montmorillonite clay turbidity was not lethal to juvenile and adult fishes at turbidities found in nature.

210. Other investigators, however, have concluded that suspended solids do interfere with gill functioning and a number of mechanisms have been suggested. Both Ellis (1937) and Trautman (1957) suggested that the silt that formed a coating in the gill cavity interferred with gas exchange and respiratory failure resulted.

211. Herbert et al. (1961) studied the effects of fine clay particles on rainbow trout (*Salmo gairdnerii*) and noted a thickening of the gill lamellae in those trout in the more turbid waters in comparison to those in clear water.

212. Kemp (1949) concluded that the adverse effect of the suspended solids clogging the gills was the abrasive action of the particles. Pautzke (1938) also observed the accumulated suspended solids in the gill cavity and attributed respiratory difficulties and suffocation to excess mucous secretion stimulated by the presence of the solids.

213. Rogers (1969) exposed several species of marine fishes to a variety of particles, including kaolin, ground rock flour, incinerator fly ash, diatomaceous earth, powdered charcoal, pulverized glass, and glass beads. After 24 hours, mortality increased as a function of exposure time and temperature, and with increased particle size and angularity. Rogers (1969) concluded that the suspended solids affected fish either by coating and clogging gills, or by abrasion of the branchial epithelium.

214. Two of the most comprehensive laboratory studies on the lethal and sublethal effects of suspended solids on estuarine fishes were by Sherk et al. (1972, 1974). Bioassays with suspensions of fuller's earth were conducted on white perch (*Morone americana*), spot (*Leiostomus xanthurus*), silversides (*Menidia menidia*), bay anchovies (*Anchoa mitchilli*), mummichogs (*Fundulus heteroclitus*), and striped killifish (*F. majalis*). Substantial mortality occurred in four of the six species at suspended solids concentrations similar to those found in natural systems during flooding, dredging, and dredged material disposal. Lethal concentrations ranged from a low of 0.58 g/ℓ fuller's earth (24-hr LC_{10}) for silversides, to 24.5 g/ℓ fuller's earth (24-hr LC_{10}) for mummichogs. Based upon these studies, fishes were placed into 3 categories: tolerant species (24-hr LC_{10} > 10.0 g/ℓ) including the mummichog, striped killifish, and spot; sensitive species (24-hr LC_{10} < 10.0 > 1.0 g/ℓ), the white perch and bay anchovy; and highly sensitive species (24-hr LC_{10} < 1.0 g/ℓ), the silversides. The bottom-dwelling species were the most tolerant of suspended solids, while the filter feeders were the most sensitive. The juveniles, within a given species, were more sensitive than the adults. Dead fish often had gills tightly packed with particles, but no pronounced gill hemorrhaging. The authors suggested that in the juveniles, where the metabolic rate is higher than in the adults, the smaller gill openings trapped more particles, inhibiting oxygen uptake.

215. Sherk et al. (1972, 1974) also investigated the sublethal effects of suspensions of fuller's earth on hematology, carbohydrate utilization, and gill histology. An examination of the gills of white

perch, following exposure to sublethal concentrations, showed evidence of tissue disruption and increased mucus production. The striped killifish and toadfish (*Opsanus tau*), exposed to less than 1.25 g/ℓ of fuller's earth for 5 days, both exhibited increases in hematocrit and the hogchoker (*Trinectes maculatus*) additionally showed an elevated red blood cell (RBC) count. Rates of liver glycogen depletion increased in hogchokers, indicating increased carbohydrate utilization during sediment stress.

216. During the same investigations (Sherk et al., 1972, 1974), preliminary studies using natural sediments indicated that suspensions of natural mud affect fish in the same way as fuller's earth, but at higher concentrations.

217. Peddicord et al. (1975) extensively studied the influence of temperature and dissolved oxygen on the lethal effects of suspended bentonite under laboratory conditions on the shiner perch (*Cymatogaster aggregata*), striped bass (*Morone saxatilis*), and English sole (*Parophrys vetulus*). In the initial experiments with the English sole in kaolin suspensions, no mortalities were observed in concentrations of 70 g/ℓ or less after 10 days of exposure. However, 80 percent mortality resulted after 10 days at 117 g/ℓ. The shiner perch was the most sensitive species studied with only one fish alive after 26 hours in 14 g/ℓ suspended kaolin.

218. In the experiments involving the influence of temperature on the lethal effects of suspended bentonite, the English sole had no deaths at 10°C in 60 g/ℓ and only one death in 60 g/ℓ at 18°C during the 10-day run. The shiner perch was again the most sensitive species tested with almost total mortality after 10 days at 10°C in 0.4 g/ℓ suspended bentonite. No striped bass mortalities occurred at 5 ppm dissolved oxygen in suspended bentonite concentrations from 0.2 to 2.0 g/ℓ and under the same conditions the shiner perch suffered only 20 percent mortality in 10 days.

219. When temperature and dissolved oxygen variations occurred simultaneously, the survival time of both the striped bass and the shiner perch was affected, indicating a complex interaction between the suspended bentonite, temperature, and dissolved oxygen. An analysis of

all variables indicated that lowest survival occurred at the higher suspended solids concentrations and low temperature and dissolved oxygen conditions.

220. The results of Peddicord et al. (1975) indicated the following: as demonstrated by Sherk et al. (1974), it was not possible to predict the magnitude of the LC_{50} from the LC_{20} or LC_{10} values; a correlation existed between normal habitat and sensitivity to suspended solids; high suspended solids concentrations would be less harmful in winter than in summer because the lower temperature would increase the solubility of oxygen in the water; and that the fishes were more sensitive to the suspended solids than any of the invertebrates studied.

221. Herbert and Merkens (1961) kept rainbow trout in the laboratory for 6 months in suspensions of kaolin and diatomaceous earth and found that while there were negligible mortalities among control fish and those in suspended solids concentrations of 30 ppm of either solid, more than half the trout in 270 and 810 ppm usually died, frequently from the effects of disease. In the intermediate concentration of 90 ppm, there were more deaths than in clean water, but the mortality was always less than 20 percent. As an important aspect of their study, Herbert and Merkens (1961) noted pathological changes in the gill tissues. The cells of the respiratory epithelium were much thicker than in normal gills and in places adjacent lamellae were fused, frequently at the tips. Similar histological changes were also noted by Jones (1962).

222. Herbert et al. (1961) investigated the status of brown trout populations in rivers which were continuously polluted with the wastes from china-clay mining. The abundance of this species in an area containing an average of 60-ppm suspended solids was about equal to that in clear control streams nearby, although the density of the trout populations in stretches containing about 1000 and 6000 ppm was only one seventh of that found in the control rivers.

223. Although the data from polluted streams (Herbert et al., 1961) and from the laboratory studies (Herbert and Merkens, 1961) show that a trout fishery is likely to be harmed if the average concentration of

suspended matter in the water is greater than about 600 ppm, Herbert and' Richards (1963) questioned the effect that average concentrations from 90 to 300 ppm might have. In laboratory tests, none of the rainbow trout died after having been exposed to 200-ppm coal-washery solids for 33 weeks. In the suspensions of wood fibre, none of the fish died in 50 or 100 ppm, but there was a slow and steady mortality among those in 200 ppm. Herbert and Richards (1963) concluded that concentrations of suspended solids in the range of 60-90 ppm often encountered in nature did not have an adverse effect upon either the survival or general health of rainbow trout.

224. Similar results and conclusions were obtained by the U. S. Fish and Wildlife Service (1970) in a study of San Francisco Bay fish. Fish were subjected to concentrations of Bay sediments producing turbidities of 500, 1500, and 2500 JTU's and changes in weight and survival were noted for up to 42 days. They concluded that only those turbidities substantially above 500 JTU's could affect the viability of the fish studied.

225. Numerous investigations have been conducted to determine the effects of dredging operations on adult fishes. Ingle (1952) studied the effect of dredging operations upon fish in Mobile Bay, Alabama. Although some fishes were observed to migrate out of the dredging area, damage to fishes was not observed, even within 25-50 yd of an active dredge. In a follow-up paper, Ingle et al. (1955) considered inorganic and organic constituents in the mud to determine possible toxic effects. No toxicant, including hydrogen sulfide, was found in the water near the disposal site. Although high suspended mud concentrations killed fish held in tanks by clogging their gills, fishes were thought to avoid these high concentrations and to be unaffected in the open bay.

226. The effects of a dredging operation on the fish of upper Chesapeake Bay were studied by Ritchie (1970). There was no apparent decline in catch of the commercially important striped bass, *Morone saxatilis*, nor did dredged material disposal increase mortalities among four species of fishes caged near the disposal site. Histological examination of the gills of 11 species of fishes prior to and following

dredging operations indicated no cell thickening or fusion of lamellae. Ritchie (1970) suggested that if shallow overboard disposal was confined to a period from December through February when fewer species were present in upper Chesapeake Bay, the least possible damage would result.

227. In a Georgia estuary, Stickney (1972) examined the effects of intracoastal waterway dredging on the ichthyofauna. The patterns of seasonal occurrence and abundance remained more consistent than even in the control stations before, during, and after dredging. No effects of dredging could be demonstrated.

228. Flemer et al. (1968) studied the biological effects of dredged material disposal in Chesapeake Bay. Monthly fish samples were obtained with an otter trawl and fish exposure experiments were conducted with cages exposed to the disposal site water. No gross effects from disposal of fine materials were observed on adult fishes held in the cages, nor did a histological examination of fish gills indicate any damage to the epithelial cells.

229. The effects of in-stream sand and gravel dredging in the upper Allegheny River were examined by Bardarik et al. (no date) during the period of 11-19 October 1971. Bardarik et al. found no substantial differences in species diversity between sites above and below the dredging operation. They did recommend, however, a process of selective dredging that would allow portions of the stream to be retained in its natural state.

230. There are a number of other factors that result in increases in turbidity and suspended material that may be harmful to fish, but are unrelated to dredging and dredged material disposal. These include industrial wastes disposal, natural disasters, and phytoplankton blooms and red tide outbreaks.

231. Ware (1970) discussed the effects of the accidental contamination of the Peace River, Florida with phosphate mine wastes. The primary component was montmorillonite clay with an average particle size of from 3 to 10 μm. The highest recorded concentration was a turbidity of 57,000 ppm that was of 2-3 days duration. It was estimated that 90 percent of the fish population was killed as a result of suffocation

due to clogged gill filaments. Wallen (1951) reported that most fishes endured turbidities of 100,000 ppm of montmorillonite clay, but these values are not consistent with those obtained by Ware (1970). This demonstrates the invalidity of optical measurements for these purposes.

232. Baumgartner et al. (1973) and Plumb (1973) discussed the effects of the discharge of 60,000 tons/day of taconite tailings on the water quality in Lake Superior. Laboratory studies cited by both authors indicated that several species of fishes commonly found in Lake Superior could survive for periods of 3 weeks in undiluted taconite tailings suspensions (23 g/ℓ) without exhibiting adverse effects. Based on their data and from data obtained from a literature survey (Lennon et al., 1968), the authors concluded that there was no evidence for a direct effect of tailings on fishes in Lake Superior.

233. A number of fish kills have been attributed to increased turbidity and suspended material as a result of natural disasters. Kemp (1949) attributed a large fish kill in the Potomac River to a flood that produced turbidity levels of 6000 ppm for 15 days. Similar results have been reported in a number of other studies.

Reproduction,
growth, and development

234. In recent years there has been more attention focused on the effects of suspended material on the reproduction, growth, and development of fishes, and Plumb (1973) provides extensive general and supplementary bibliographies on the subject. Although several of these studies are now rather old, much of their data and findings are still valid. In his study on the effect of taconite tailings on lake trout spawning in Lake Superior, Plumb (1973) was unable to relate most past studies on spawning to the Lake Superior situation. The majority of the studies were concerned with lotic habitats in which solids were discharged into a river and gradually flushed downstream. In Lake Superior the wastes were not thoroughly mixed with the receiving water nor were the wastes as mobile. Plumb (1973) could only conclude that because the discharge occurred in less than 1 percent of the lake, any direct physical impacts from taconite tailings disposal would be

confined to the immediate discharge zone.

235. Buck (1956) was one of the first investigators to study the direct effects of turbidity and suspended sediment on fish reproduction and growth. At the end of a 2-year study, he found that the average total weight of fishes in clear farm ponds was about 1.7 times greater than in ponds of intermediate turbidity and 5.5 times greater than in muddy ponds. Of the three species used, large-mouth bass were most affected by turbidity in both growth and reproduction. The most turbid pond in which bass reproduced had an average turbidity equivalent to that produced by 84 ppm standard silica flour, while the redear sunfish and bluegills spawned successfully in ponds having turbidities equivalent to about 180 ppm silica flour. In hatchery ponds, high turbidities reduced growth and total yield of both bass and bluegills, but increased channel catfish production.

236. In a study in Chesapeake Bay, Flemer et al. (1968) examined the effects of dredging and open water disposal on fish eggs and larvae. No gross effects from disposal of fine material were observed on eggs and fish larvae.

237. In a more recent quantitative study, the effects of suspended Chesapeake Bay sediments on the eggs of several species of estuarine fishes were examined by Schubel and Wang (1973). Laboratory experiments were conducted in which eggs of four species of fishes (yellow perch, white perch, striped bass, and alewife) were incubated in suspensions of varying concentrations of natural, fine-grained sediment. Concentrations of up to 500 mg/ℓ had no statistically significant effect on the hatching success of eggs of all four species, although at concentrations above 100 mg/ℓ there was frequently a delay of several hours in the time of hatching. Schubel and Wang (1973) concluded that in nature in a relatively well-mixed environment, concentrations of natural fine-grained suspended sediment up to about 500 mg/ℓ would not affect hatching success of the four species studied.

238. Morgan et al. (1973) also studied the effects of suspended sediment on the eggs and larvae of white perch and striped bass from upper Chesapeake Bay. While Schubel and Wang (1973) found that

concentrations above 100 mg/ℓ delayed hatching, Morgan et al. (1973) found that delayed development for the white perch and striped bass occurred only in concentrations above 1500 mg/ℓ. Particle concentrations greater than 4000 mg/ℓ delayed hatching up to one day for the white perch. The 2-day LC_{50} for striped bass and white perch larvae were 3411 mg/ℓ and 2679 mg/ℓ, respectively.

239. Dovel and Edmunds (1971) found a shifting in the site of spawning of striped bass in upper Chesapeake Bay. They attributed this shift to the construction of dams along the Susquehanna River and the creation of a favorable habitat in the Elk River through the enlargement of an adjacent canal. The currents characteristic of striped bass spawning grounds suspend the eggs and prevent siltation. Clean, viable eggs were collected from an area of the canal that was the site of dredging operations. The water, except in the immediate vicinity of the dredge, rarely had concentrations of suspended sediment in excess of 200 mg/ℓ.

240. Swenson and Matson (1976) studied the influence of red-clay turbidity on the laboratory survival, growth, and distribution of larval lake herring (*Coregonus artedii*). The larvae were held for 62 days in 9 concentrations of suspended solids varying from 1 to 28 mg/ℓ, which produced turbidities of 0-48 Formazin Turbidity Units (FTU). Test concentrations were designed to include the natural turbidity range of the red clay area in western Lake Superior. Growth and survival were not influenced at the range of concentrations studied. Larvae in the higher concentrations were distributed closer to the surface of the test tanks. Swenson and Matson (1976) suggested that if such a change in vertical distribution occurred in Lake Superior, it might indirectly influence survival.

Miscellaneous effects

241. While most research has concentrated on the lethal and physiological effects of turbidity and suspended solids, several behavioral effects have also been noted. Heimstra et al. (1969) studied the effects of silt turbidity (4-16 JTU's) on behavior of juvenile largemouth bass (*Micropterus salmoides*) and green sunfish (*Lepomis cyanellus*). The activity of bass was substantially reduced by turbidity while sunfish

activity was reduced only slightly. Feeding and agonistic (attack) behavior were not influenced. Scraping behavior of both species was higher under turbid conditions as the fishes vigorously rubbed their bodies against the bottom or sides of the aquarium. There was evidence that turbidity disturbed normal social hierarchies in green sunfish. Heimstra et al. (1969) also noted that both bass and sunfish in the higher turbidities tended to frequently engage in what might be described as "coughing." Heimstra et al. (1969) suggested that the fishes in the turbid conditions were attempting to free their gills of silt. Similar reactions were described by Lagler et al. (1977) and Southgate (1960). The general reduction in activity that was observed by Heimstra et al. (1969) was thought to reduce the fishes' ability to locate food and increase their susceptibility to predation.

242. Turbidity and suspended solids concentrations lower than those necessary to cause death or physiological injury may also produce other responses. Guebitz (1966) found that several substances elicited a fright response from rainbow trout. Concentrations ranged from 27 gm/ℓ for soapstone to 1500 mg/ℓ for kaolin. A fright response has also been reported for other mining wastes by Ingle et al. (1955) and Saunders and Smith (1965).

243. Another potential effect of increases in turbidity and suspended solids is to cause a shift in species composition from game fish to rough fish. Trautman (1957) cited changes in Ohio drainages where species complexes dominated by fishes requiring clear and/or vegetated waters were replaced by those dominated by species tolerant of much more turbid waters. He also noted a shift from large, commercially important fishes to smaller species "unfit as human food." Changes of this nature require long-term alterations in turbidity levels and may be reversible if the turbidity is reduced at a later date (Lee and Plumb, 1974).

244. Although turbidity and suspended solids can have a number of adverse effects on fishes, there are also several beneficial effects which are primarily related to the increased concealment offered by turbidity. Cairns (1968), Griffin (1938), Herbert and Merkens (1961),

and Hollis et al. (1964) noted that turbid water can act as a screen to reduce predation by other fishes.

245. Stroud (1967), however, reported that the increased concealment afforded to the fish by turbidity could be detrimental to game fishes. Increased turbidity could result in a slower growth rate, because game fishes tend to feed by sight, and several investigators (Griffin, 1938; Herbert and Richards, 1963; Kramer and Smith, 1965; Smith et al., 1966) have recorded reduced growth rates and weights among several species of fishes in turbid waters.

246. Bennett et al. (1940), Buck (1956), and Hollis et al. (1964) pointed out that fishing success decreases in more turbid waters and while this may not be advantageous to sportsmen, it is beneficial to the fish. Because of the sorption tendencies of most suspended solids, large amounts of suspended solids could detoxify water (Plumb, 1973). By sorbing a toxic chemical from solution, the suspended solids would make it unavailable to the fish.

247. Finally, several authors, after having observed dredging in a particular area, felt that dredging and the resultant increases in suspended solids were beneficial to fishes. Viosca (1958) attributed the congregation of fishes near dredges in Louisiana to the dredges stirring up food and nutrients.

PART V: EVALUATIVE SUMMARY AND CONCLUSIONS

248. Efforts to quantify turbidity have resulted in numerous definitions, units of measure, and methods of measurement. The term turbidity has been defined in a number of different ways. As a result, it has been suggested (McCluney, 1975; National Oceanographic Instrumentation Center (NOIC), 1974; Pickering, 1976) that the term turbidity should be considered only as a relative nontechnical appearance descriptor to be used much in the same manner as the term "warmth." While retaining the term turbidity only as a descriptor, when a measurement is made it should be directly related to a fundamental optical quantity and reported in precise, scientifically identifiable terminology.

249. The practice of calibrating the various instruments for the measurement of turbidity in JTU's, FTU's, NTU's, or ppm can also be misleading. There is general agreement (McCluney, 1975; NOIC, 1974; Pickering, 1976) that the optical instruments in current use provide an inferred and not a direct measurement of suspended solids. Their use for this purpose must be supported by ancillary measurements which can demonstrate that the optical measurement is correlated with the concentrations of the particular material to be measured. However, as noted by Pickering (1976) and others, it is almost impossible to transfer the relationships between sediment concentrations and optical characteristics from one environment, type of turbidimeter, or type of sediment to another. Variations may be as much as 500 percent (Hach, 1974). Thus, calibrations with the same standard (Formazin) and units of measurement (FTU's, JTU's, or NTU's) have unwittingly resulted in correlations between unrelated numbers. Instrument-to-instrument comparison may be possible only if the optical characteristics for scattering instruments, the angles of measurement, size and shape of beam, spectral distribution of the energy utilized, etc. are known.

250. One of the major concerns with regard to the protection of an aquatic fauna from lethal suspended sediment concentrations is the amount of solids in suspension that can potentially settle out as flow decreases--i.e., settleable solids (Duchrow and Everhart, 1971). For

these purposes, turbidity is a questionable measure of suspended solids in water. For direct animal impacts or sedimentological considerations, optical measurements are irrelevant. An accurate index would be suspended solids measured gravimetrically. For photosynthetic or aesthetic considerations, optical measurements may be preferable.

251. Suspended material can be introduced to or resuspended in an aquatic environment by nature (floods, storms, winds, tides) or by man (dredging, filling, dumping). As recognized by Biggs (1968), Vittor (1972, 1973), and others, high turbidity and suspended sediment levels in lakes and bays that are a result of natural processes frequently have more impact on the aquatic environment than dredge effluents or suspended sediments from other human activities. In his review of the environmental effects of hydraulic dredging in estuaries, May (1973) also summarized the characteristics and parameters associated with the dredging operations themselves. Although in one study a measurable turbidity plume was detected 3 miles downstream from the discharge location, this value was considered to be unusual because the turbidity plume generally becomes indistinguishable within 2000 ft of the discharge site (May, 1973). May (1973) also reported that turbidity increases are usually within normal fluctuations at sampling sites greater than 400 ft from the disposal operations and that the durations of the turbidity elevations are rather short. Some of the studies reported background levels two hours after the disposal of dredged material had ceased.

252. Dredging activities can be major sources of suspended sediments in waterways. Many of the studies on effects of dredging and disposal of dredged material on water quality have only been concerned with the most obvious effect, turbidity, and still represent rather diverse points of view. Available data indicate that most suspended sediments, especially dredged material, are very heterogeneous, but do not differentiate between soluble, available, and total forms of an element (Lee and Plumb, 1974). If the potential effect of suspended material on water quality is to be determined, this distinction must be made.

253. There is general agreement in the literature that the release of aquatic plant nutrients from bottom sediments can and does occur

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(Lee et al., 1975). The release of nutrients from resuspended bottom sediments has been cited as a potential adverse effect of dredging activities because of the possibility that the nutrients might stimulate algal blooms and red tides. However, the relative importance of the various physical, biological, and chemical mechanisms by which nutrients might be released is still being disputed.

254. Austin and Lee (1973) concluded that lake sediments act as sinks because of the inadequate mixing that occurs at the sediment-water interface. Thus dredging operations might provide the energy necessary for more complete mixing and this could affect the potential of sediments to release nutrients.

255. The importance of and beneficial role that suspended materials play in sorbing and removing contaminants from the water column have been discussed by numerous investigators. Therefore, the potential effects of dredging on water quality would not necessarily be adverse to the ecosystem. Dredging that resulted in increased water circulation and suspended material could produce improved water quality under certain conditions. Many authors believe that increased turbidity levels caused by dredging activities do not represent a significant water quality problem because such turbidity is a transient condition that only exists in a limited area and lasts only a few hours. This is especially true in estuaries and the open ocean where the fine particles will settle at faster rates because of agglomeration and flocculation (Windom, 1973).

256. When dredging and/or the disposal of dredged material is planned, legitimate questions arise about the effects of turbidity and suspended sediments on aquatic organisms. The organisms that may be influenced by dredging activities include phytoplankton, rooted aquatic vegetation, invertebrates and fishes. The effects that suspended solids may have on organisms are dependent upon composition, sorbed minerals or toxins, and tolerance of the organisms themselves when exposed to the suspended material, as well as concentration of the suspension. Because the effects are due to several factors, Sherk (1972) concluded that it is possible that concentration standards may be of relatively

little significance for assessing biological effects of suspended solids. As indicated by the available data from some of the older field studies, it is often very difficult to assess the effects of particle size and concentration of suspended solids on aquatic organisms independent of, and in addition to, complicating factors associated with natural sediments such as sorbed toxic metals and pesticides, biochemical oxygen demand (BOD), and nutrient content. Thus, the objective of most recent laboratory studies has been to identify the biological effects of particulate material similar in size distribution to those sediments likely to be found in natural systems, but free of numerous complicating variables.

257. Turbidity and suspended material can exert both beneficial and detrimental influences on the primary productivity of aquatic plants, although only general conclusions have been reached as to the exact nature of the effect. The most frequently cited negative effect is the reduced photosynthetic activity due to interference of light penetration. Cordone and Kelley (1961) associated a decrease in aquatic plants in Lake Erie over a 50-yr period to an increase in turbidity. However, in several of the studies cited, at a given depth, there was no direct relationship between photosynthesis and turbidity. High natural background levels of turbidity, as a result of winds and currents, can also markedly limit primary production. Edmondson (1956) discussed the relationship between the photosynthetic rate of phytoplankton and light intensity in lakes and noted that light can vary over a wide range of intensity without proportional variations of photosynthesis.

258. The addition of suspended material through natural processes and/or human activities can indirectly stimulate photosynthesis. Turbid mixtures containing inorganic material can raise nutrient levels thereby promoting primary production. Most of the studies that considered the effects of dredging and disposal of dredged material on primary production concluded that the reduced water transparency was of short duration and that these activities resulted in little change or minor, temporary release of nutrients.

259. The responses of aquatic animals (primarily economically important species) to a variety of particles, including processed and

natural sediments, have been studied under both laboratory and field conditions. Unfortunately, because of the differences in methodologies employed and the expression of data, comparison of results is often difficult. Few of the previous studies have related animal responses to actual weight per volume concentration of particles in suspension. Most investigators correlated response with turbidity, which is an optical property of water containing suspended material, although it is unlikely that the light absorbing and scattering properties of suspended particles directly affect animals (Peddicord et al., 1975). Kunkle and Comer (1971) pointed out that turbidity produced by particulate matter is dependent upon particle size, shape, mineralogy, and color, and that there is no predictable correlation between turbidities produced by equal weight/volume concentrations of different materials.

260. Numerous investigators discussed the detrimental aspects of large quantities of silt and sand on the distribution, reproduction, and abundance of benthic aquatic invertebrates. However, in most of these older studies the results are probably attributable to siltation, rather than suspended solids effects, because no distinction was made between these two factors, which are distinctly different.

261. With the exception of a few commercially important species, little is known about the effects of turbidity and suspended material on aquatic invertebrates. Most of the studies that have dealt with the effects of temporary increases in turbidity and suspended material on invertebrates, such as those areas where dredging and the disposal of dredged material has occurred, concluded that there were no permanent effects exhibited. As might be expected, the group most frequently affected includes the filter-feeding invertebrates. A number of investigators concluded that the energy expended for food gathering could exceed the energy obtained from that food. The imposition of a suspended load stress on filter feeders could seriously affect the rate of water transport, the efficiency of the filtering mechanism, and increase the amount of energy needed for maintenance alone as the organisms compensated for the additional stress (Sherk, 1971). However, with the return to natural conditions, the normal pumping rates are ususally resumed.

262. In their literature reviews, Cordone and Kelley (1961) and the EIFAC (1964) noted that it is difficult to assess the effects of turbidity and suspended material on fishes because other conditions frequently affect fishes before and during the increase in suspended solids. As noted by Peddicord et al. (1975), the effects of turbidity and suspended solids on fishes may be the result of a complex interaction between the solids themselves and other parameters such as temperature and dissolved oxygen. Saunders (1963), studying the biological characteristics of fresh water, stated that no single environmental factor is ever controlling or limiting to the ecosystem, but rather there is a multiplicity of factors. Single factors are usually masked by other factors which are operating simultaneously. Most of the cause and effect relationships are generalizations derived by inferences from experimental investigations under controlled laboratory conditions and applied to observations performed in the field (Saunders, 1963). Any effects are also a function of the type of solid, length of contact time, species of fish, condition of the fish, and age of the fish.

263. In addition, laboratory experiments often do not duplicate natural conditions or reflect natural levels of tolerance. Several investigators (Ingle et al., 1955; Sherk et al., 1972, 1974) demonstrated that natural or dredging-related suspensions of sediments that were toxic to fishes in the laboratory produced no detectable changes when encountered in the same concentrations by the same species of fishes in nature. In several studies, in order to produce given rates of mortality or severity of sublethal physiological change, higher concentrations of resuspended natural sediments were required to cause the same effects that were obtained with suspensions of commercial mineral solids of known composition, particle size distribution, and organic matter content. Other laboratory investigators concluded that fishes were capable of surviving concentrations of suspended solids considerably higher than those encountered under natural conditions or as a result of man's activities, such as dredging and the disposal of dredged material. Thus it can be difficult to predict the results of increased suspended solids concentrations on fishes based on laboratory findings.

264. Laboratory results for some of the more recent studies have been reported in terms of the lethal concentration (LC) in grams per liter per unit time, usually 24 hours. However, because the relationship between lethal concentration and lethal exposure time is not linear, it is not possible to extrapolate lethal values for other exposure times from the experimental results. The importance of this becomes obvious when relating exposure times to those likely during dredging and disposal, which are typically of short duration.

265. Experiments conducted in a laboratory environment can obviously differ from the conditions in nature. As pointed out by Peddicord et al. (1975), the use of an open system allowing relatively undisturbed long-term testing under carefully monitored physical conditions, coupled with frequent biological observations permitting determination of rates of effect, overcomes many major concerns about laboratory research and results. Herbert and Merkens (1961) also considered this when they questioned how far the results of a laboratory study were directly applicable to the survival of animals in waters polluted with inert solid material. They concluded that a stress that reduced survival chances in one environment would probably reduce them to some extent in another, although not necessarily to the same degree.

266. Many of the studies reviewed seem to indicate that a wide variety of species can tolerate increased concentrations of suspended material, such as those encountered during the disposal of dredged material, and that most changes which do occur are reversible. A number of investigators have suggested additional guidelines for dredging operations and the disposal of dredged material that would further help to minimize the effects of suspended material. The "controlled dredging" suggested by Ingle (1952) was elaborated upon by Cronin (1970) in the summary to his extensive study on the effects of dredging in upper Chesapeake Bay. He proposed the following: careful planning should be instituted when large-scale environmental modifications are planned in areas that serve as valuable nursery grounds; the disposal sites of fine sediments should be far enough away so that future, natural movements of these sediments through lateral fluid flow or resuspension would not

become a problem; and since estuaries are particularly vital nursery grounds, special consideration should be given to eggs and larvae in these areas.

267. Cairns (1968) also pointed out that all environmental conditions operative at the time of dredging and disposal of dredged material must be considered because organisms are often capable of compensating for one stress if no other stressful conditions are present. He also suggested that regulatory standards for increased suspended solids should be based on natural variation and background levels and should differ to reflect various types of waters.

268. Flemer et al. (1968) suggested that year round field studies and laboratory studies are required to rationally determine the biological effects of increased suspended solids due to dredged material disposal. As an example, Flemer et al. (1968) reported a 33 percent reduction in productivity that lasted several hours following dredging in Chesapeake Bay while the natural diurnal variation of productivity that was observed was 300 percent. Thus studies at the time of dredging would only indicate the presence or absence of extreme damage to the ecosystem at that point in time but might not be indicative of natural mortality patterns.

269. Sherk et al. (1972) pointed out that the use of lethal concentration levels to establish suspended solids criteria ignores the biologically significant sublethal effects of suspended solids on aquatic organisms. Therefore, it is necessary in the establishment of criteria to consider the sublethal effects of suspended material on the most sensitive species from the project area.

270. Several authors (Flemer et al., 1968; Peddicord et al., 1975) substantiated the fact that the effects of high suspended solids concentrations vary during the year and are related to fluctuating physicochemical factors (temperature, dissolved oxygen, salinity) and the biology of the organisms (reproductive strategies, migrations, etc.). Therefore, dredging and the disposal of dredged material would have the least damaging effect on the aquatic environment if conducted in light of this information.

271. The literature indicates that large amounts of naturally occurring suspended material are not uncommon in many bodies of water and do not appear to endanger, and may even favor, the development of many species (Cairns, 1968). It is also evident that the normal suspended solids concentrations of a particular stream or lake vary considerably. Since enough aquatic organisms survive temporary exposure to rather high concentrations of suspended solids to perpetuate the species, Cairns (1968) proposed relating suspended solids standards to the variations and conditions to which the aquatic species have become adjusted.

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